US009730078B2

(12) **United States Patent**
Nixon et al.

(10) **Patent No.: US 9,730,078 B2**
(45) **Date of Patent: Aug. 8, 2017**

(54) **CONFIGURING AND OPTIMIZING A WIRELESS MESH NETWORK**

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(73) Assignee: **FISHER-ROSEMOUNT SYSTEMS, INC.**, Round Rock, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/201,734**

(22) Filed: **Aug. 29, 2008**

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Related U.S. Application Data

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(51) **Int. Cl.**
H04W 16/18 (2009.01)
H04L 12/24 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04W 16/18*** (2013.01); ***H04L 41/12*** (2013.01); ***H04L 41/22*** (2013.01); *H04L 45/122* (2013.01);
(Continued)

(58) **Field of Classification Search**
None
See application file for complete search history.

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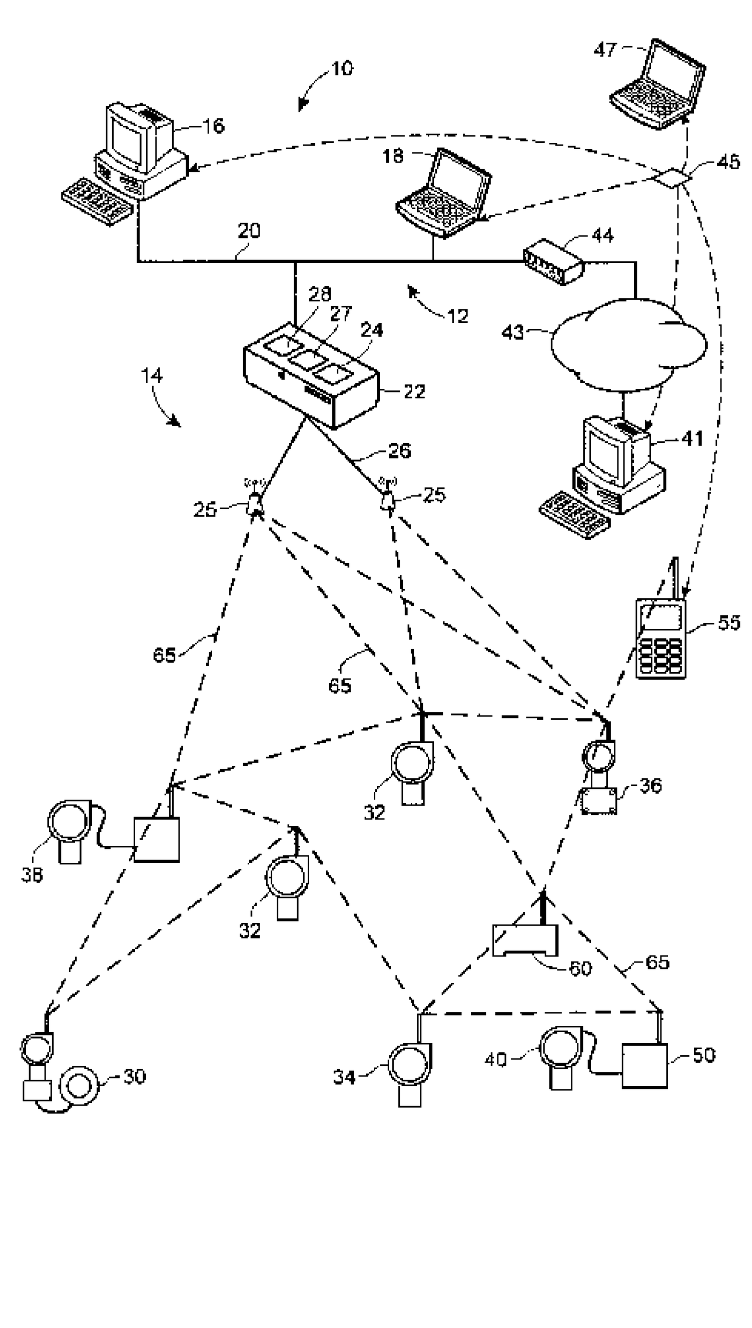
Primary Examiner — Rina Pancholi

(74) *Attorney, Agent, or Firm* — Marshall, Gerstein & Borun LLP

(57) **ABSTRACT**

An interactive software-based network design tool that may be used to simulate and view the operation of a wireless mesh device network used in a process plant, such as a wireless HART device network, allows a user to create a model of a wireless network, input several design requirements, and automatically generate and view communication routes and schedules for the wireless network. The network design tool provides an interactive graphic interface for the addition, removal, and positioning of nodes and devices within the wireless network and a menu including several interactive screens for specifying threshold values, network topology selections, routing preferences, and other configuration parameters related to generating and optimizing communication routes and schedules within the wireless mesh network. The network design tool automatically applies a set of optimization rules along with the parameters input by user to the network model in order to generate efficient network configuration data.

61 Claims, 22 Drawing Sheets



(51) **Int. Cl.**

H04L 12/733	(2013.01)
H04W 40/10	(2009.01)
H04W 40/16	(2009.01)
H04W 84/18	(2009.01)

(52) **U.S. Cl.**

CPC *H04W 40/10* (2013.01); *H04W 40/16* (2013.01); *H04W 84/18* (2013.01); *Y02B 60/50* (2013.01); *Y02P 90/18* (2015.11); *Y02P 90/185* (2015.11); *Y02P 90/20* (2015.11); *Y02P 90/26* (2015.11)

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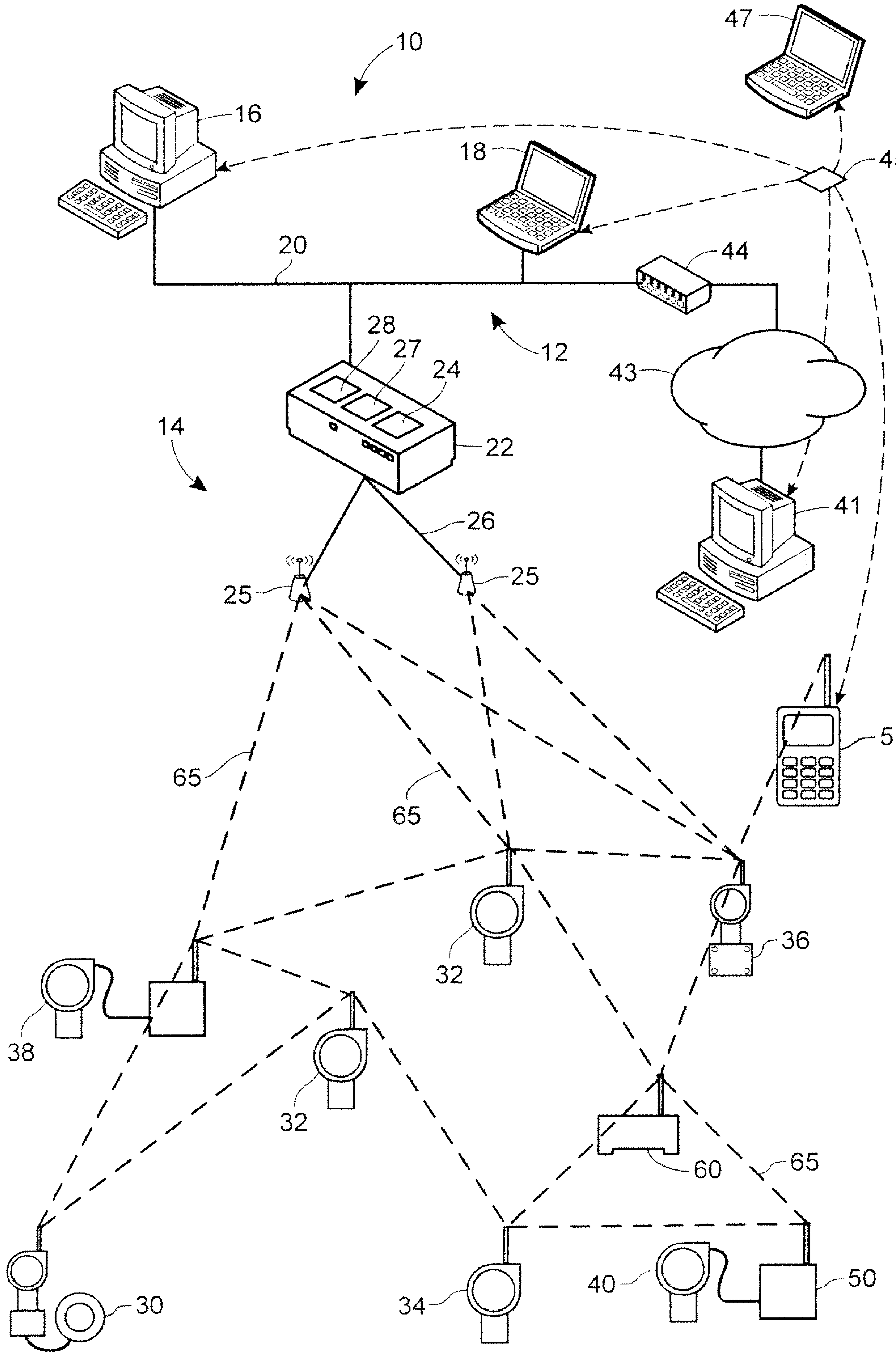
FIG. 1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16
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FIG. 2

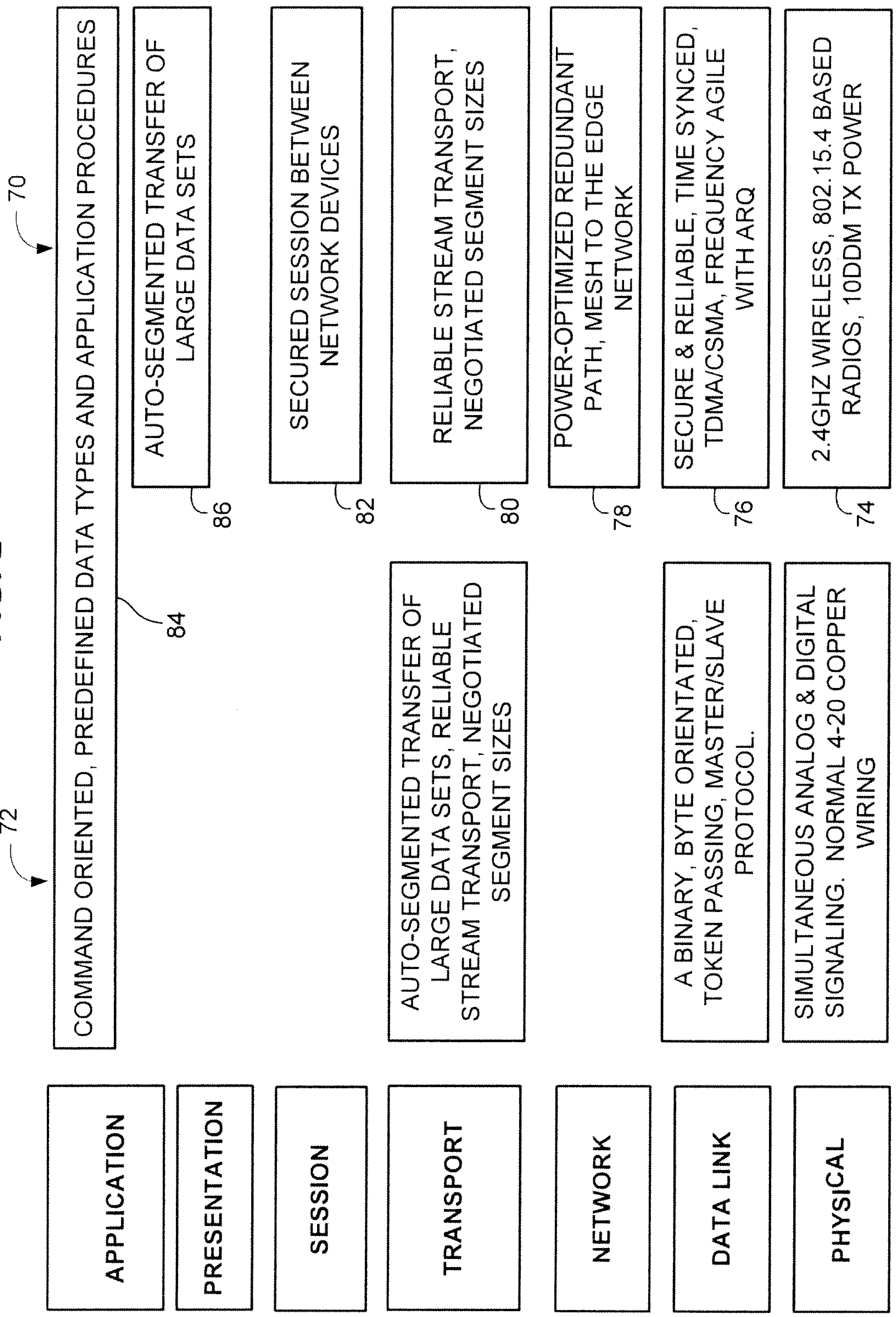
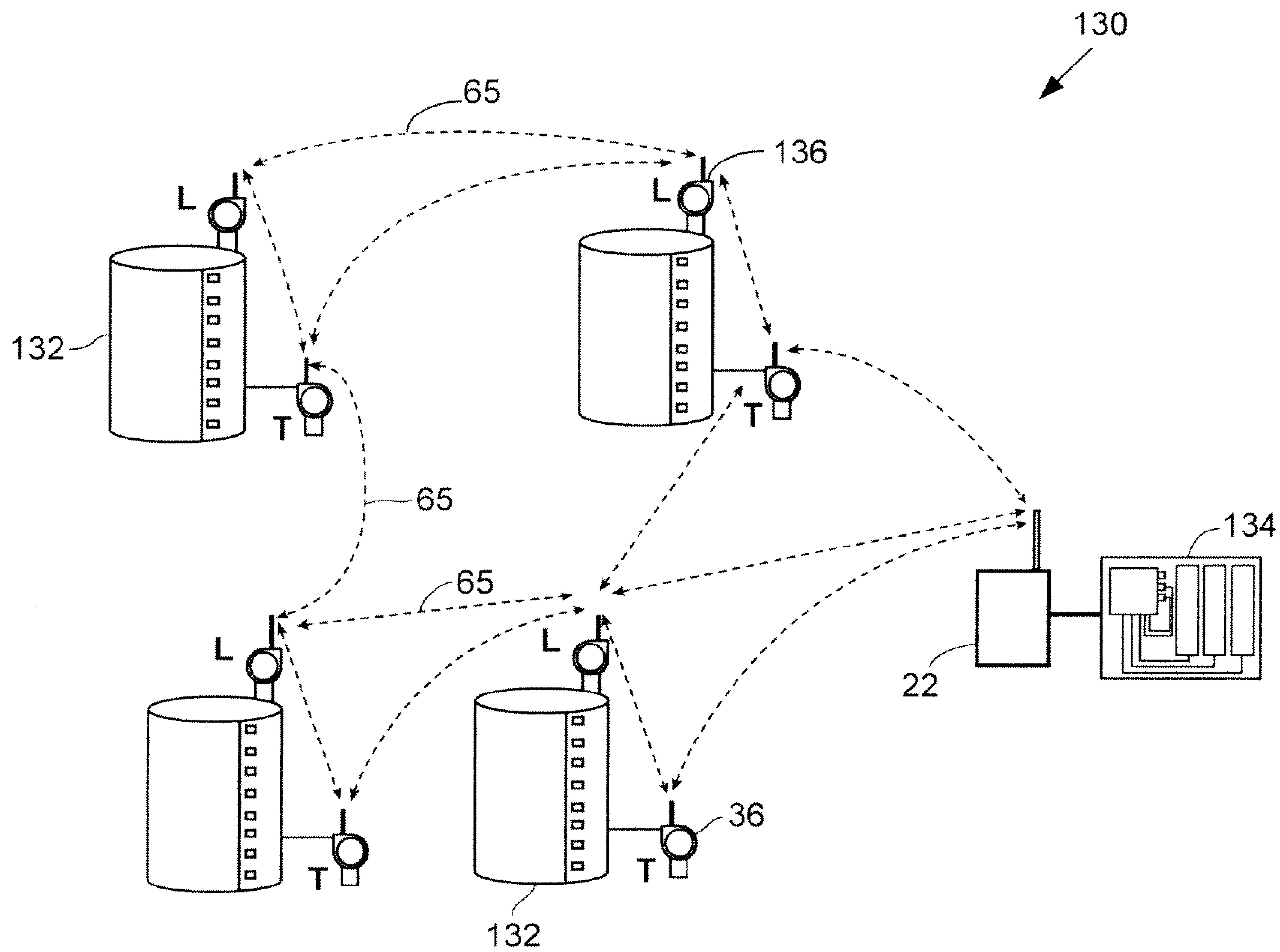

70
72
APPLICATION
COMMAND ORIENTED, PREDEFINED DATA TYPES AND APPLICATION PROCEDURES
84
PRESENTATION
AUTO-SEGMENTED TRANSFER OF LARGE DATA SETS
86
SESSION
SECURED SESSION BETWEEN NETWORK DEVICES
82
TRANSPORT
AUTO-SEGMENTED TRANSFER OF LARGE DATA SETS, RELIABLE STREAM TRANSPORT, NEGOTIATED SEGMENT SIZES
RELIABLE STREAM TRANSPORT, NEGOTIATED SEGMENT SIZES
80
NETWORK
POWER-OPTIMIZED REDUNDANT PATH, MESH TO THE EDGE NETWORK
78
DATA LINK
A BINARY, BYTE ORIENTATED, TOKEN PASSING, MASTER/SLAVE PROTOCOL.
SECURE & RELIABLE, TIME SYNCED, TDMA/CSMA, FREQUENCY AGILE WITH ARQ
76
PHYSICAL
SIMULTANEOUS ANALOG & DIGITAL SIGNALING. NORMAL 4-20 COPPER WIRING
2.4GHZ WIRELESS, 802.15.4 BASED RADIOS, 10DDM TX POWER
74

FIG. 3



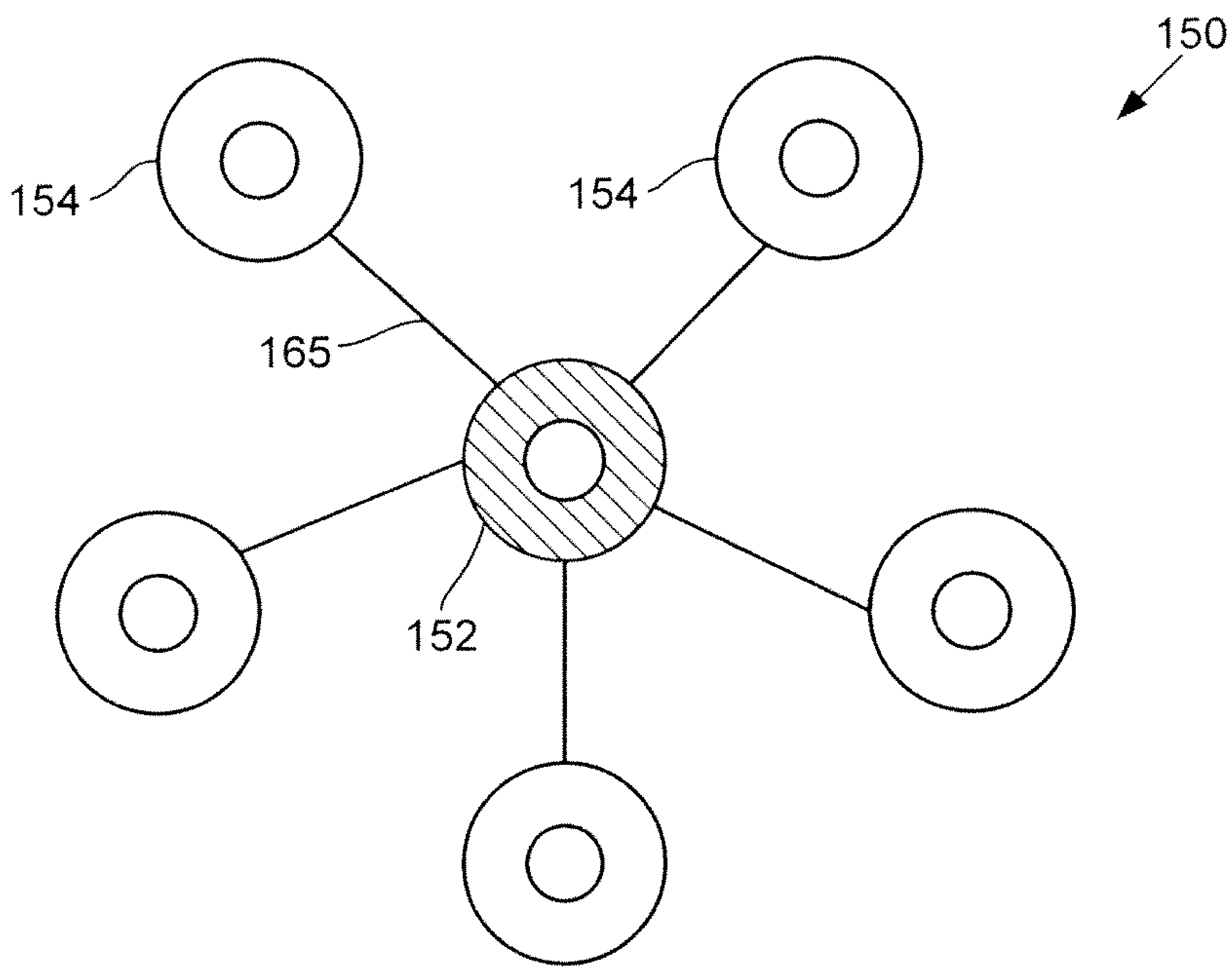


FIG. 4

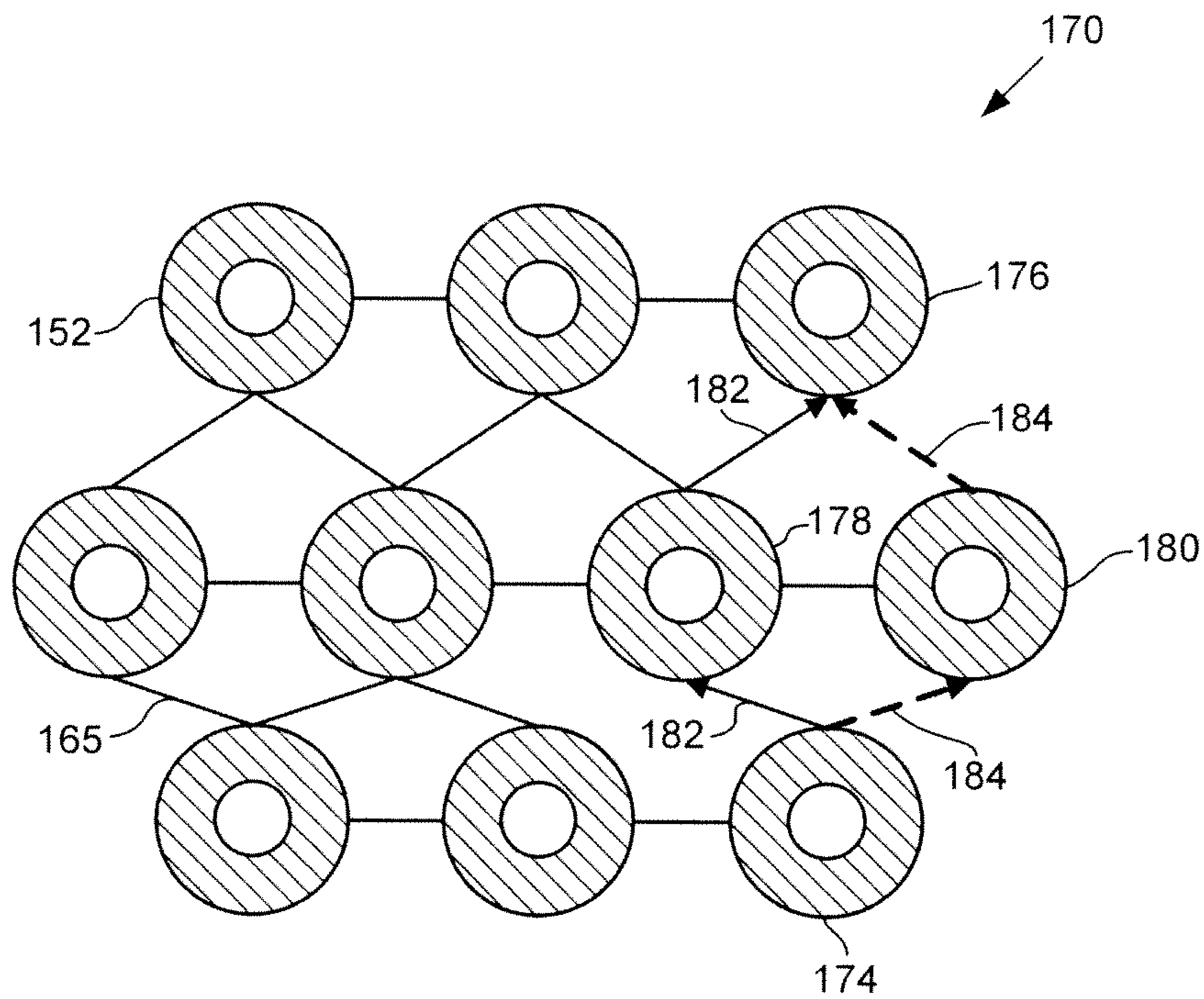


FIG. 5

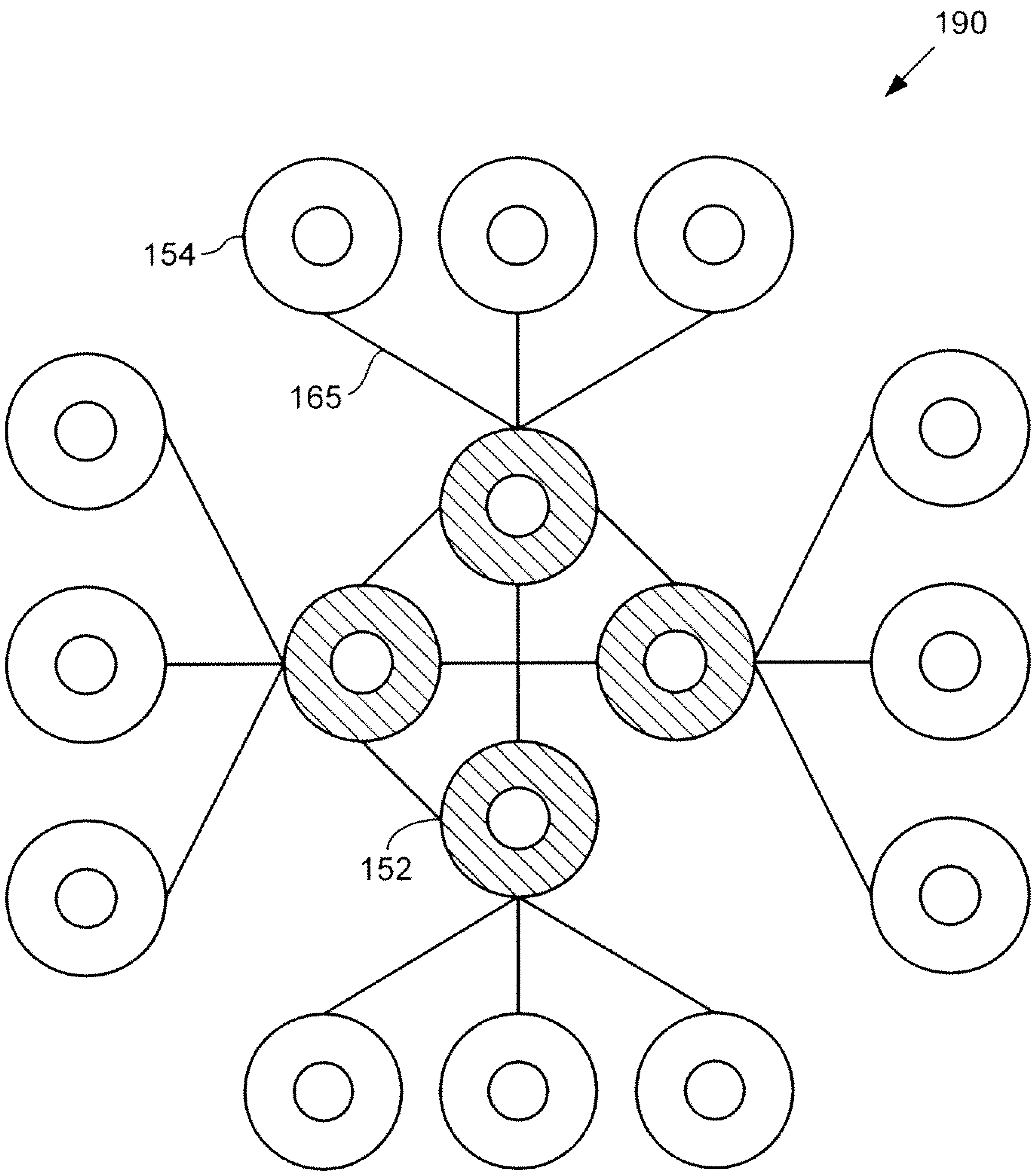


FIG. 6

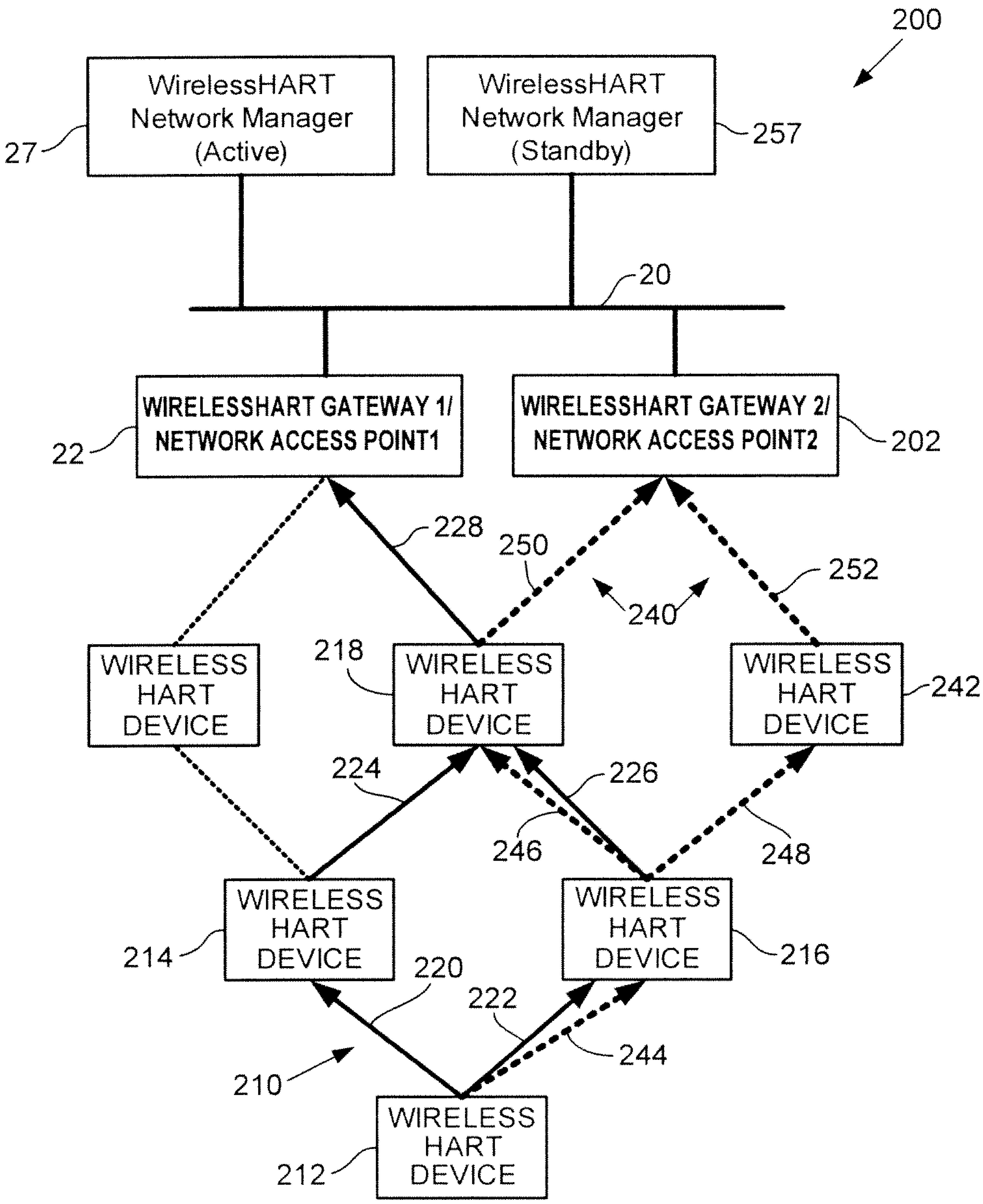

200
WirelessHART
Network Manager
(Active)
27
WirelessHART
Network Manager
(Standby)
257
20
WIRELESSHART GATEWAY 1/
NETWORK ACCESS POINT1
22
WIRELESSHART GATEWAY 2/
NETWORK ACCESS POINT2
202
228
250
252
240
WIRELESS
HART
DEVICE
218
WIRELESS
HART
DEVICE
WIRELESS
HART
DEVICE
242
224
226
246
248
WIRELESS
HART
DEVICE
214
WIRELESS
HART
DEVICE
216
220
222
244
210
WIRELESS
HART
DEVICE
212

FIG. 7

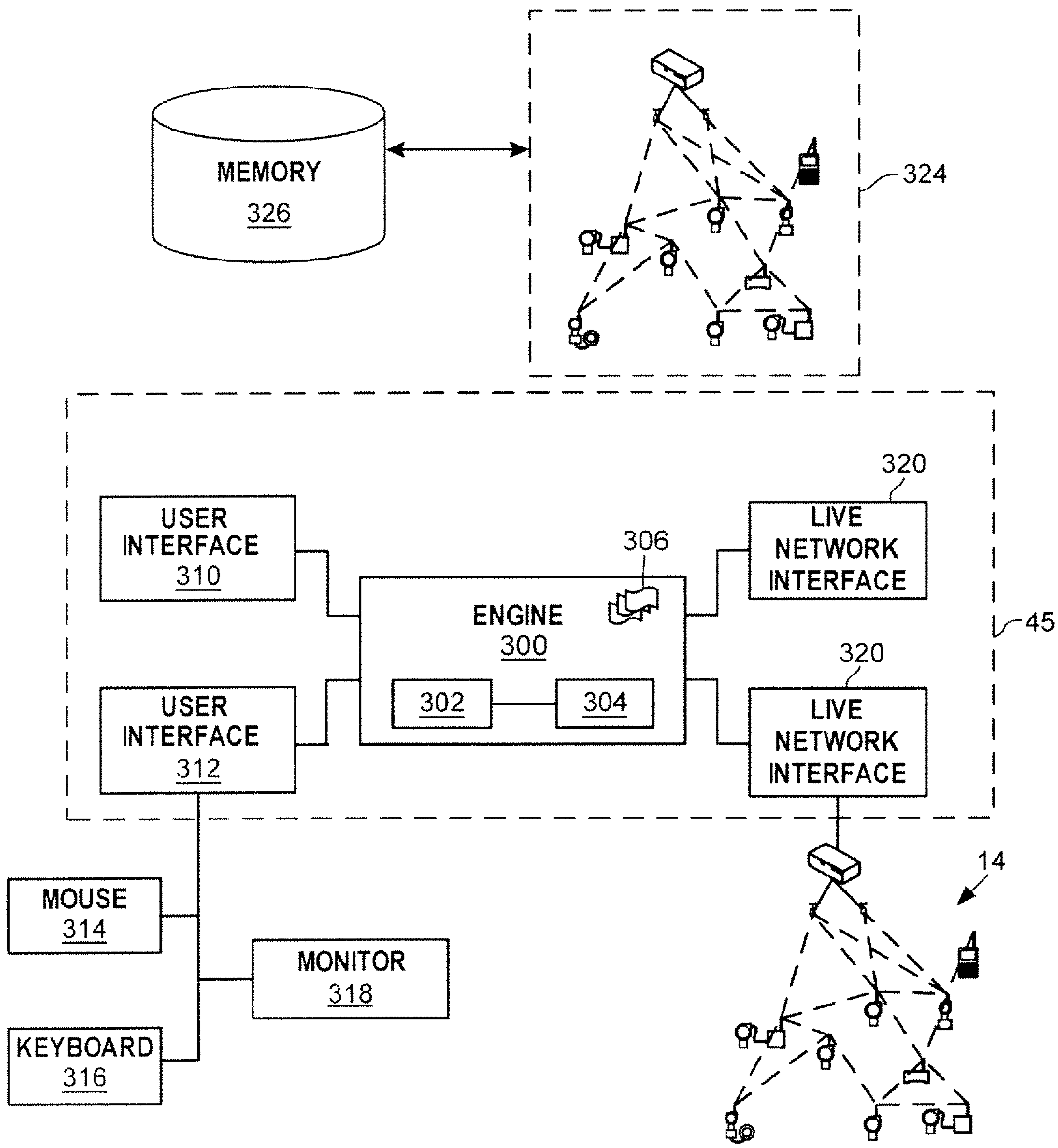

MEMORY
326
324
USER INTERFACE
310
306
ENGINE
300
302
304
LIVE NETWORK INTERFACE
320
45
USER INTERFACE
312
LIVE NETWORK INTERFACE
320
MOUSE
314
MONITOR
318
KEYBOARD
316
14

FIG. 8

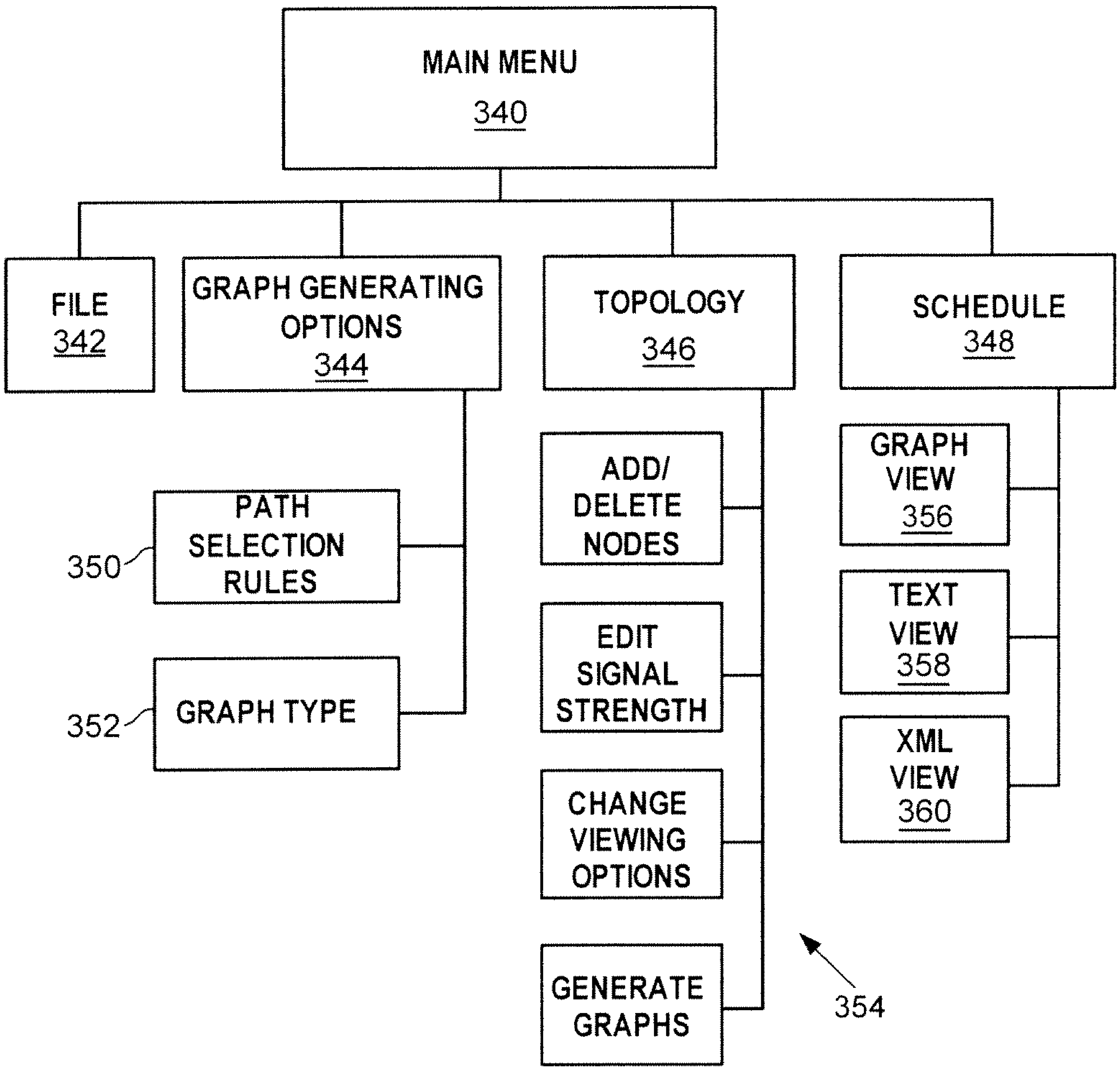

MAIN MENU
340
FILE
342
GRAPH GENERATING OPTIONS
344
TOPOLOGY
346
SCHEDULE
348
PATH SELECTION RULES
350
GRAPH TYPE
352
ADD/ DELETE NODES
EDIT SIGNAL STRENGTH
CHANGE VIEWING OPTIONS
GENERATE GRAPHS
354
GRAPH VIEW
356
TEXT VIEW
358
XML VIEW
360

FIG. 9

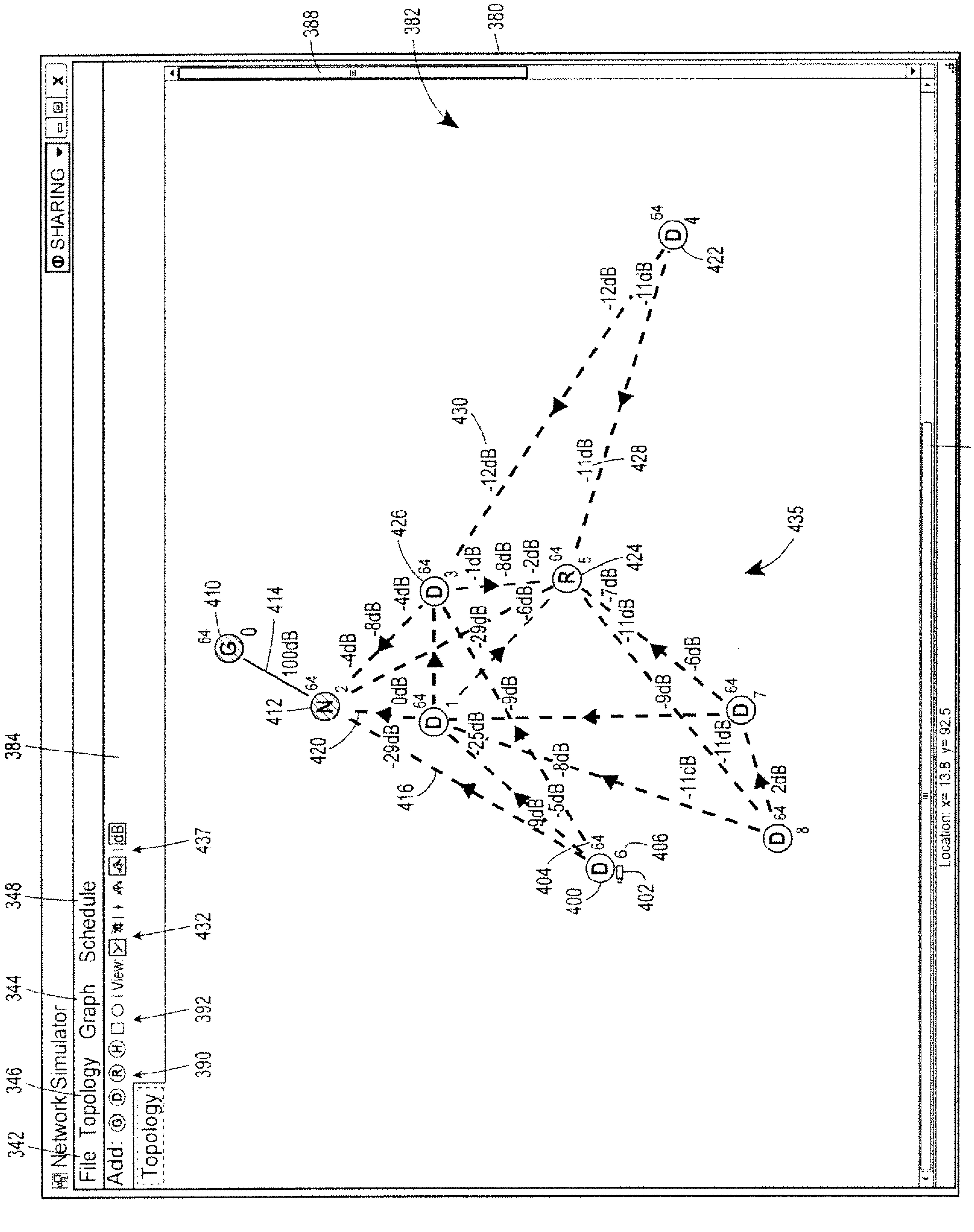

Network/Simulator
SHARING
File Topology Graph Schedule
Add:
View
Topology
Location: x= 13.8 y= 92.5

FIG. 10

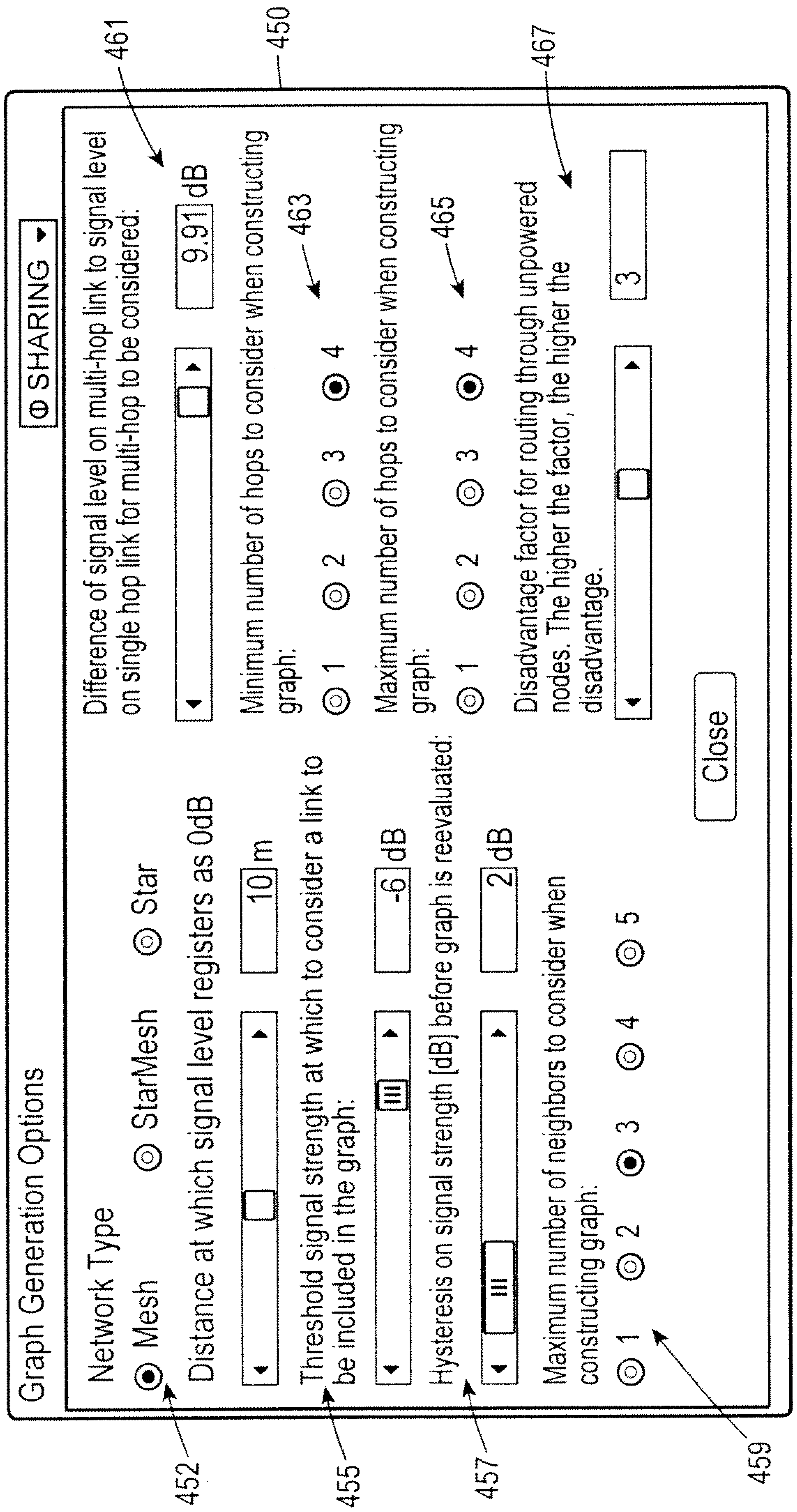

Graph Generation Options
SHARING
Network Type
Mesh
StarMesh
Star
Distance at which signal level registers as 0dB
10 m
Threshold signal strength at which to consider a link to be included in the graph:
-6 dB
Hysteresis on signal strength [dB] before graph is reevaluated:
2 dB
Maximum number of neighbors to consider when constructing graph:
1 2 3 4 5
Difference of signal level on multi-hop link to signal level on single hop link for multi-hop to be considered:
9.91 dB
Minimum number of hops to consider when constructing graph:
1 2 3 4
Maximum number of hops to consider when constructing graph:
1 2 3 4
Disadvantage factor for routing through unpowered nodes. The higher the factor, the higher the disadvantage.
3
Close
450
452
455
457
459
461
463
465
467

FIG. 11

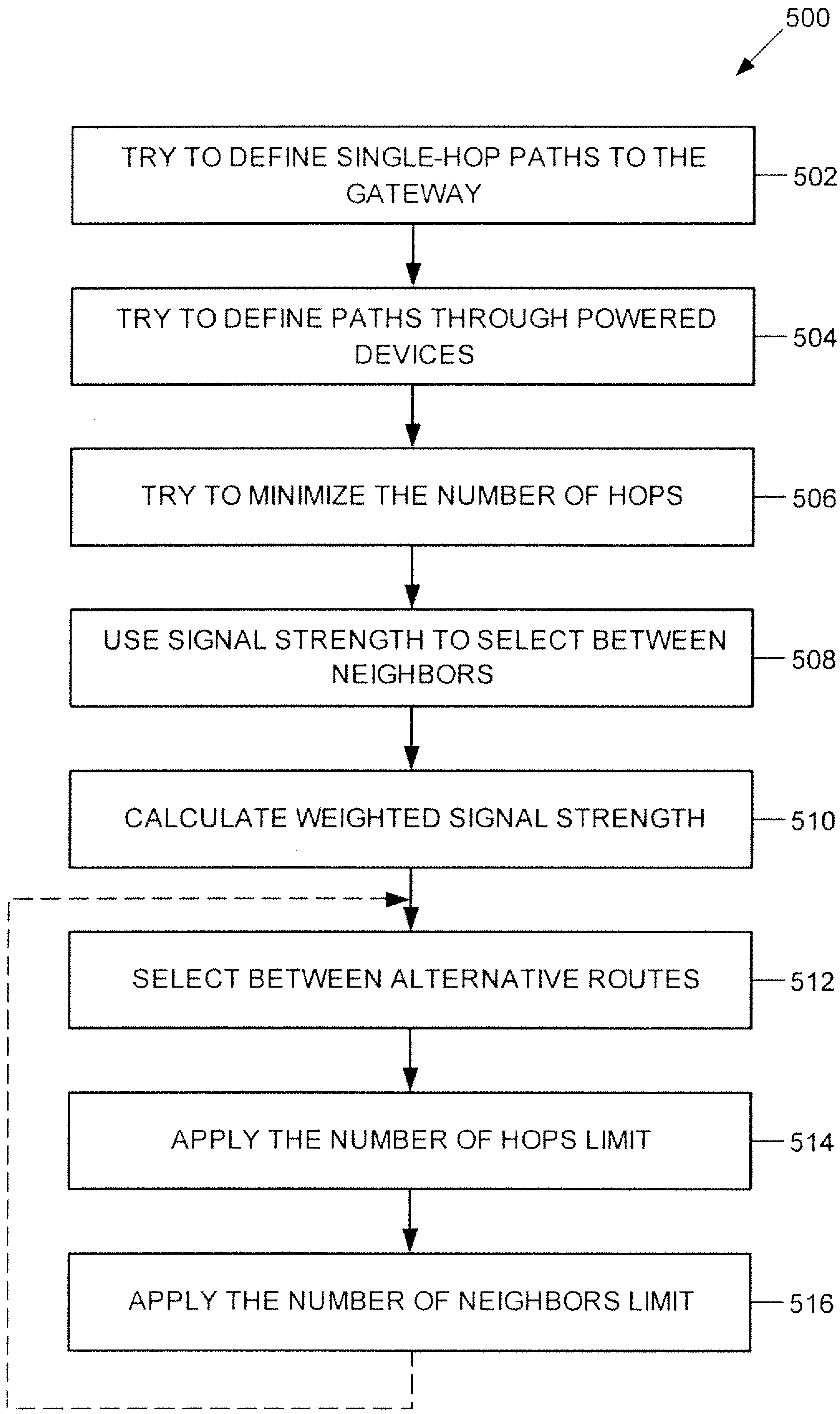

500
TRY TO DEFINE SINGLE-HOP PATHS TO THE GATEWAY
502
TRY TO DEFINE PATHS THROUGH POWERED DEVICES
504
TRY TO MINIMIZE THE NUMBER OF HOPS
506
USE SIGNAL STRENGTH TO SELECT BETWEEN NEIGHBORS
508
CALCULATE WEIGHTED SIGNAL STRENGTH
510
SELECT BETWEEN ALTERNATIVE ROUTES
512
APPLY THE NUMBER OF HOPS LIMIT
514
APPLY THE NUMBER OF NEIGHBORS LIMIT
516

FIG. 11A

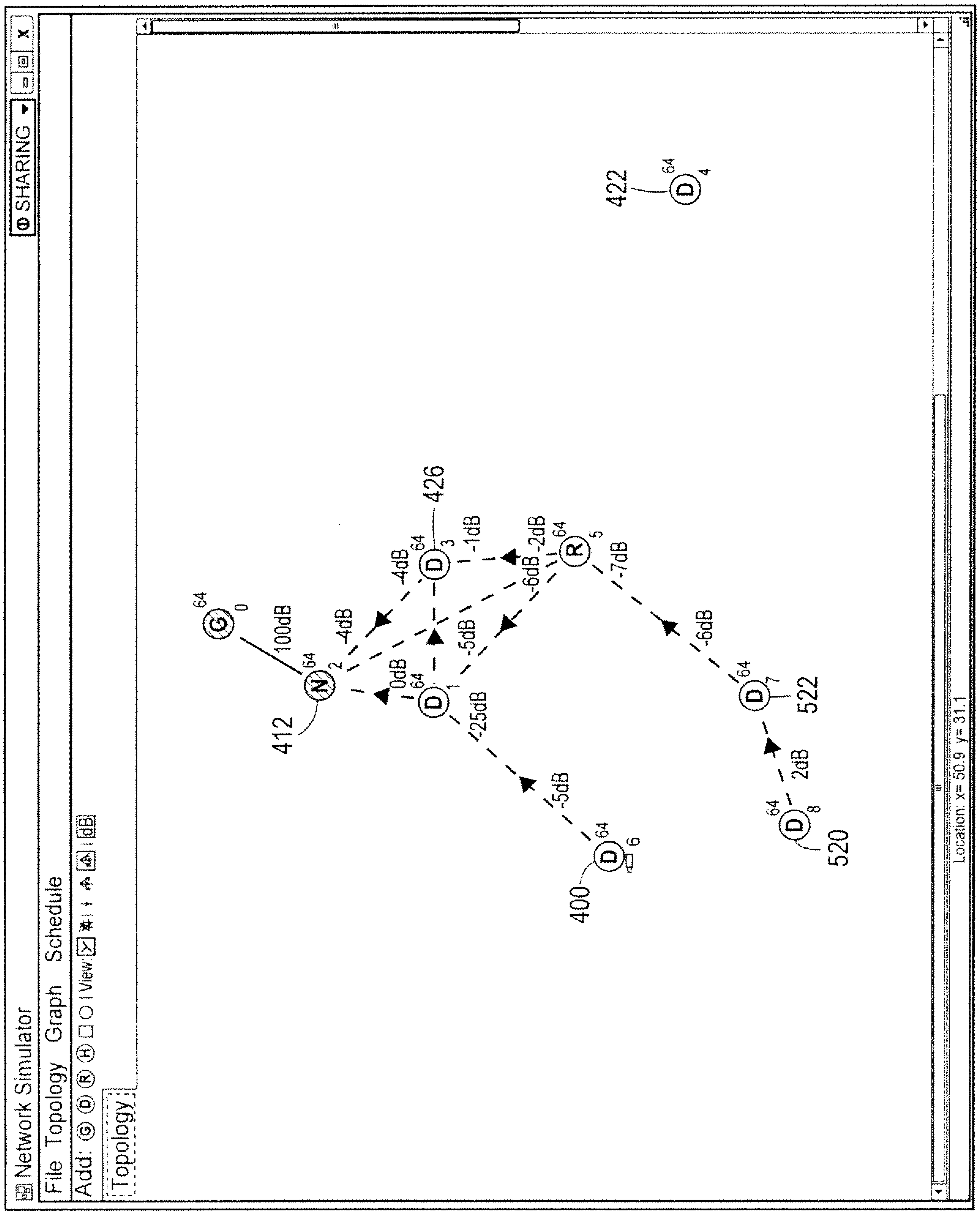

Network Simulator
SHARING
File Topology Graph Schedule
Add:
View:
Topology
100dB
-4dB
-4dB
-1dB
-2dB
-6dB
-5dB
0dB
-25dB
-5dB
-7dB
-6dB
2dB
412
426
422
400
520
522
Location: x= 50.9 y= 31.1

FIG. 12

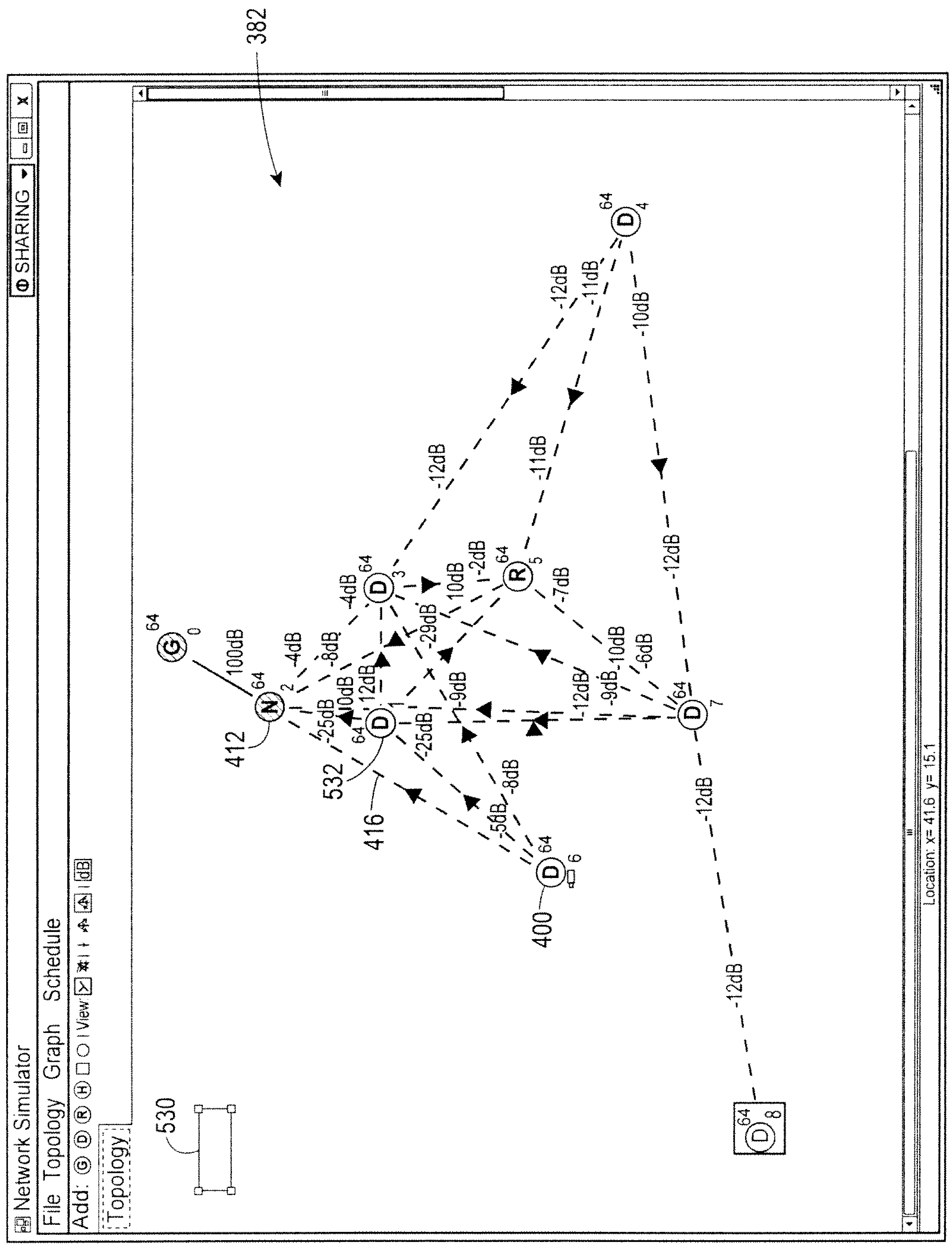

Network Simulator
File Topology Graph Schedule
SHARING
Add:
View:
Topology
382
530
412
532
416
400
100dB
-4dB
-8dB
-12dB
-10dB
-11dB
-25dB
-29dB
-9dB
-2dB
-7dB
-6dB
-5dB
Location: x= 41.6 y= 15.1

FIG. 13

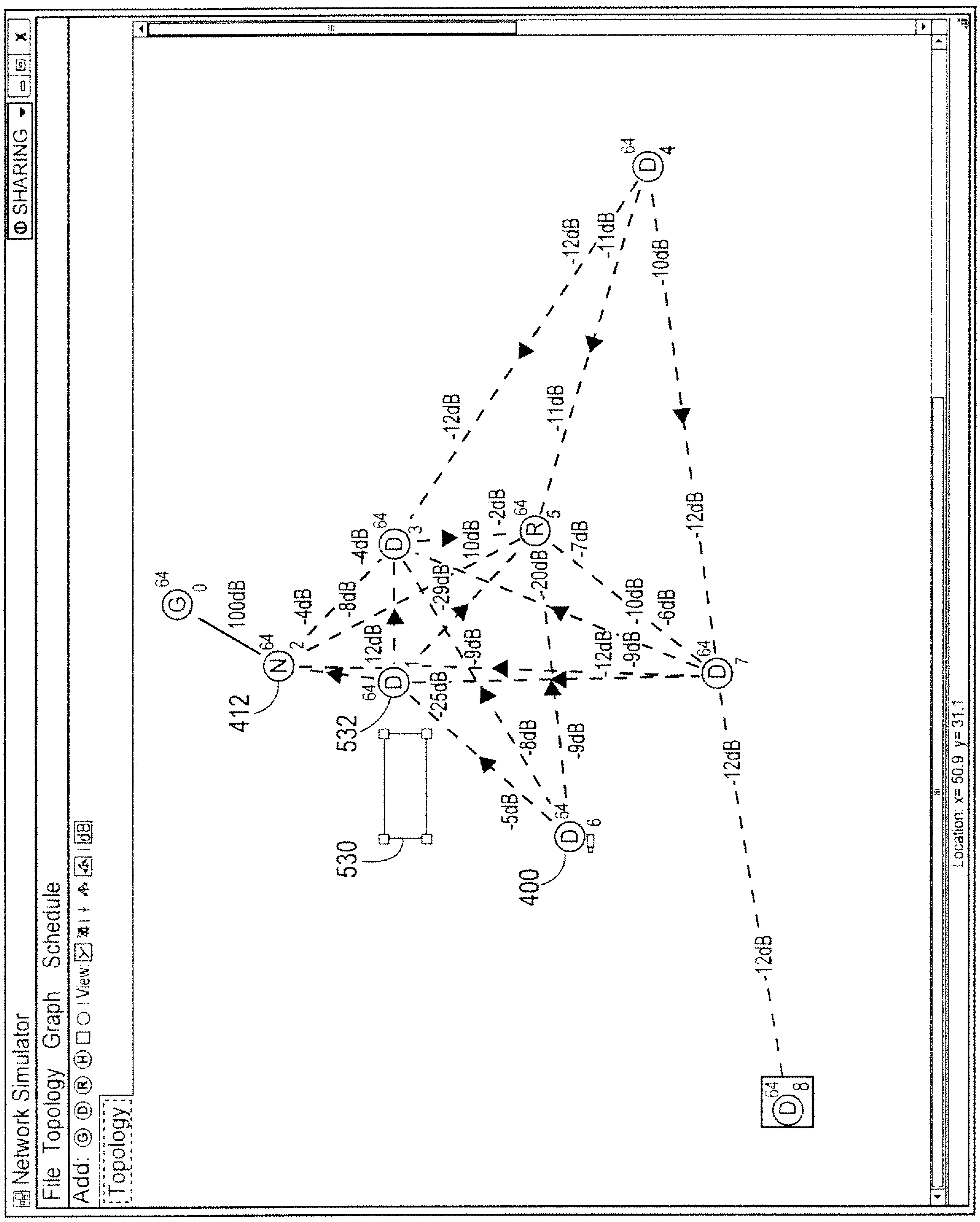

Network Simulator
File Topology Graph Schedule
Add:
Topology
SHARING
100dB
-12dB
-11dB
-10dB
-4dB
-8dB
-2dB
-7dB
-20dB
-29dB
-25dB
-9dB
-6dB
-5dB
412
532
530
400
Location: x= 50.9 y= 31.1

FIG. 14

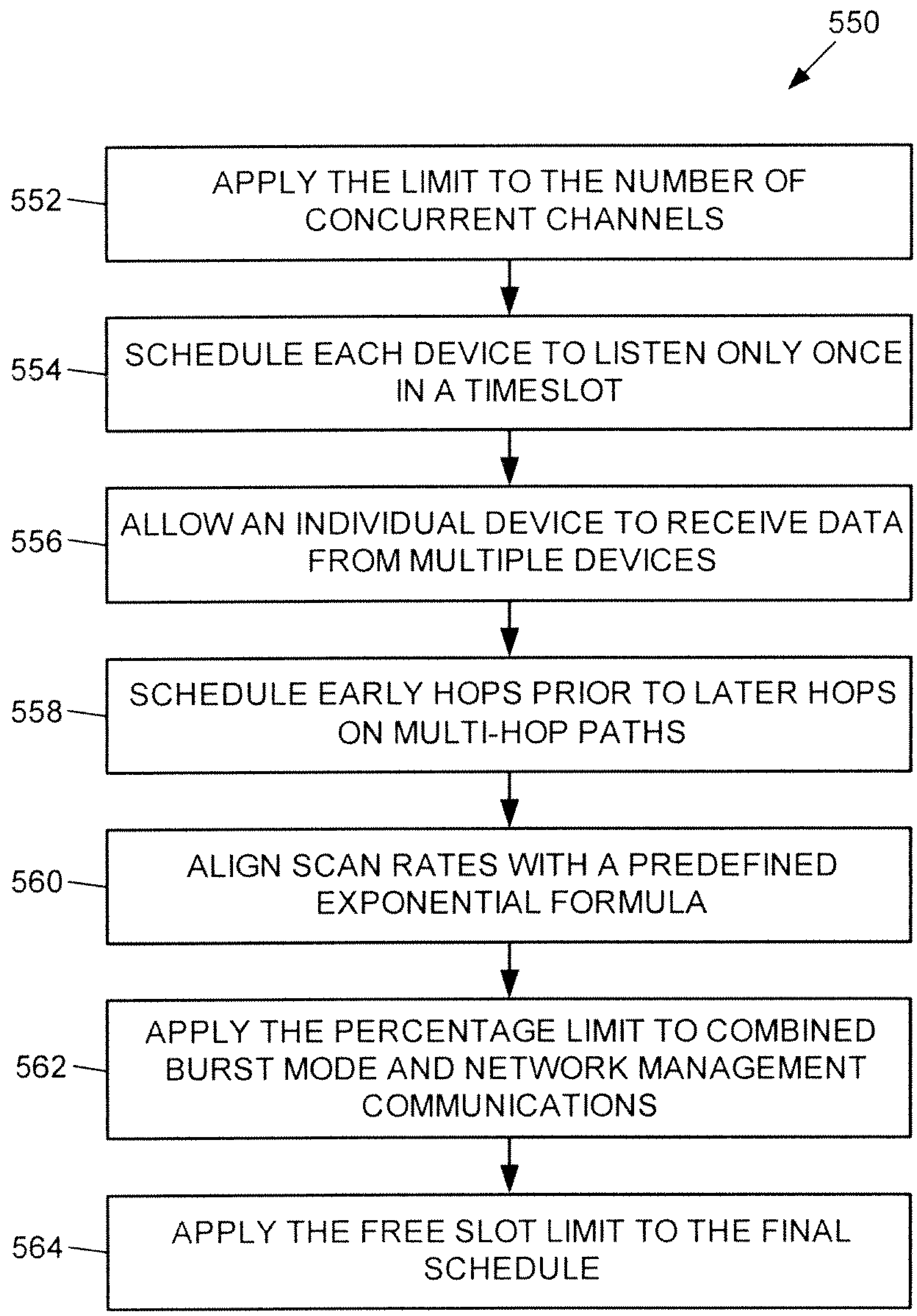

550
552
APPLY THE LIMIT TO THE NUMBER OF CONCURRENT CHANNELS
554
SCHEDULE EACH DEVICE TO LISTEN ONLY ONCE IN A TIMESLOT
556
ALLOW AN INDIVIDUAL DEVICE TO RECEIVE DATA FROM MULTIPLE DEVICES
558
SCHEDULE EARLY HOPS PRIOR TO LATER HOPS ON MULTI-HOP PATHS
560
ALIGN SCAN RATES WITH A PREDEFINED EXPONENTIAL FORMULA
562
APPLY THE PERCENTAGE LIMIT TO COMBINED BURST MODE AND NETWORK MANAGEMENT COMMUNICATIONS
564
APPLY THE FREE SLOT LIMIT TO THE FINAL SCHEDULE

FIG. 14A

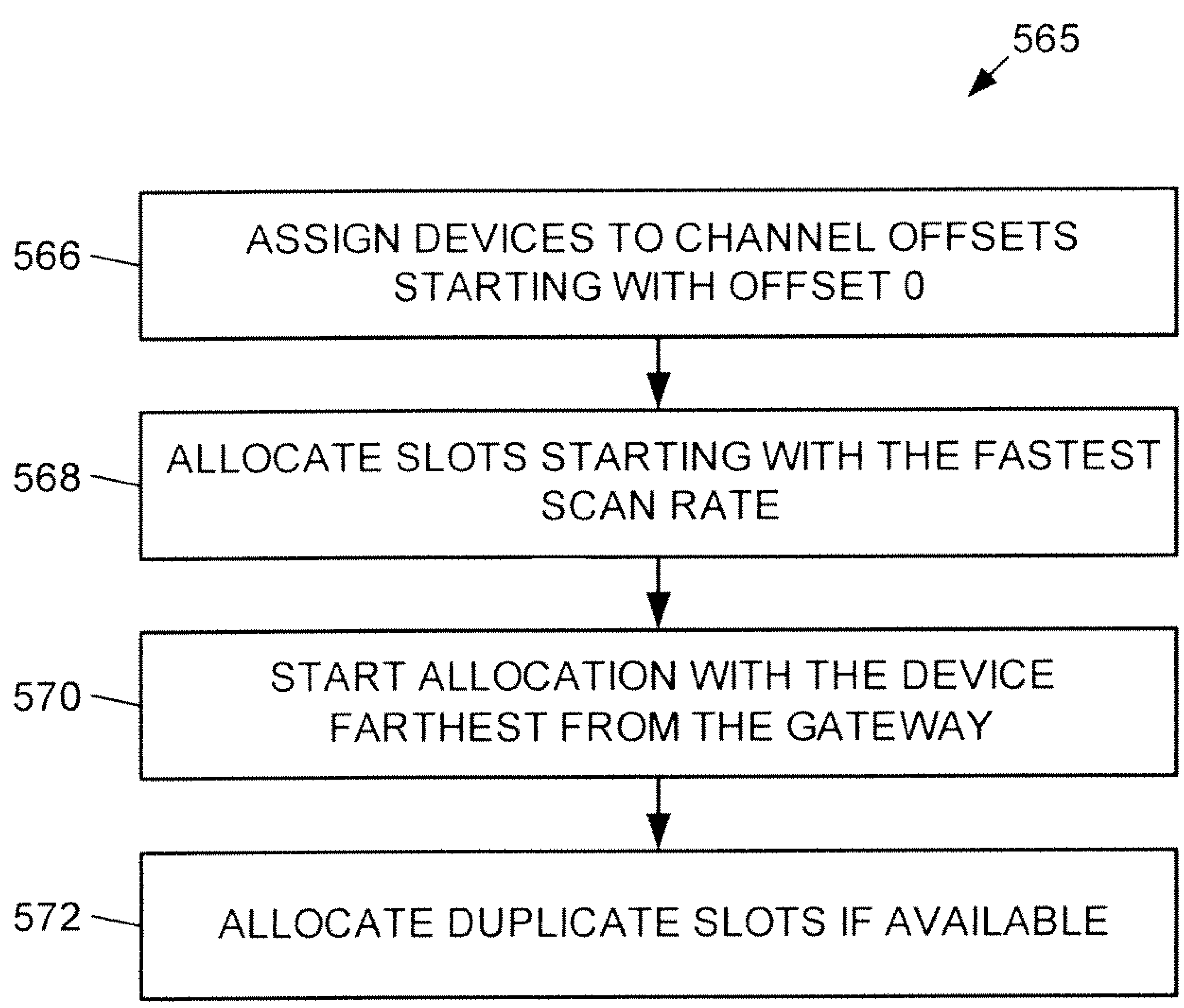

565
566
ASSIGN DEVICES TO CHANNEL OFFSETS STARTING WITH OFFSET 0
568
ALLOCATE SLOTS STARTING WITH THE FASTEST SCAN RATE
570
START ALLOCATION WITH THE DEVICE FARTHEST FROM THE GATEWAY
572
ALLOCATE DUPLICATE SLOTS IF AVAILABLE

FIG. 14B

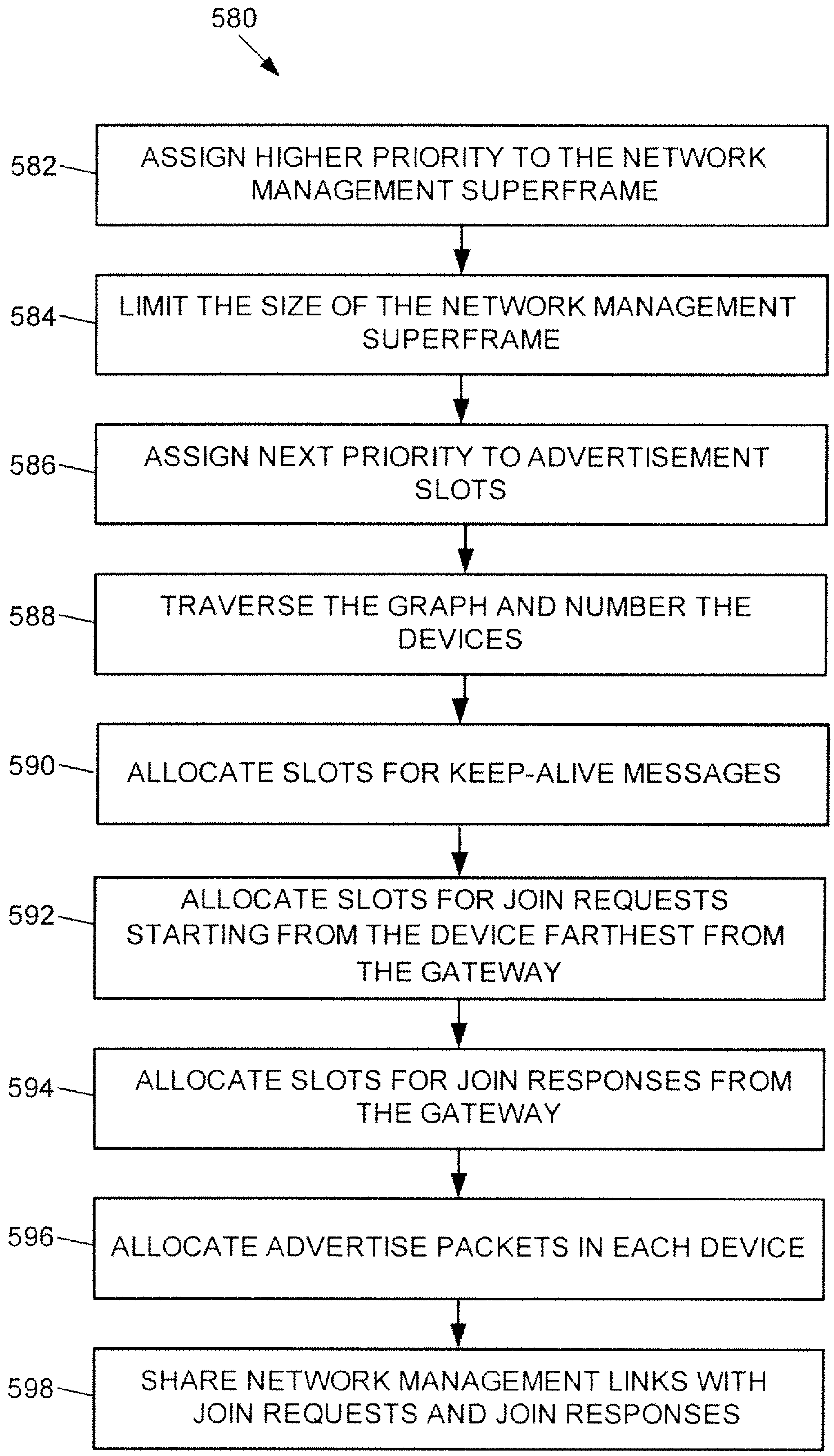

580
582
ASSIGN HIGHER PRIORITY TO THE NETWORK MANAGEMENT SUPERFRAME
584
LIMIT THE SIZE OF THE NETWORK MANAGEMENT SUPERFRAME
586
ASSIGN NEXT PRIORITY TO ADVERTISEMENT SLOTS
588
TRAVERSE THE GRAPH AND NUMBER THE DEVICES
590
ALLOCATE SLOTS FOR KEEP-ALIVE MESSAGES
592
ALLOCATE SLOTS FOR JOIN REQUESTS STARTING FROM THE DEVICE FARTHEST FROM THE GATEWAY
594
ALLOCATE SLOTS FOR JOIN RESPONSES FROM THE GATEWAY
596
ALLOCATE ADVERTISE PACKETS IN EACH DEVICE
598
SHARE NETWORK MANAGEMENT LINKS WITH JOIN REQUESTS AND JOIN RESPONSES

FIG. 14C

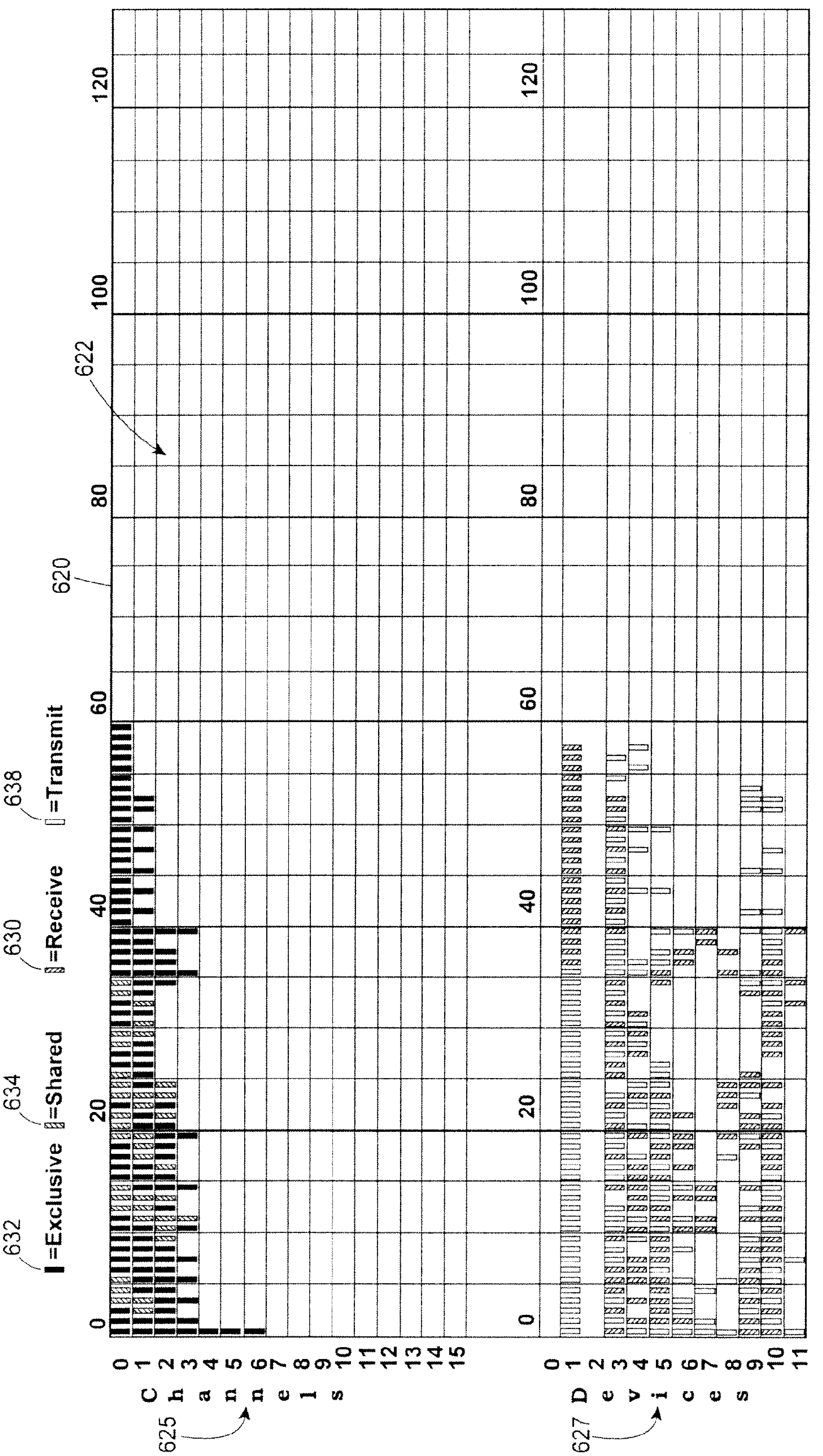

632
=Exclusive
634
=Shared
630
=Receive
638
=Transmit
620
622
0
20
40
60
80
100
120
Channels
625
Devices
627
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 1 2 3 4 5 6 7 8 9 10 11

FIG. 15

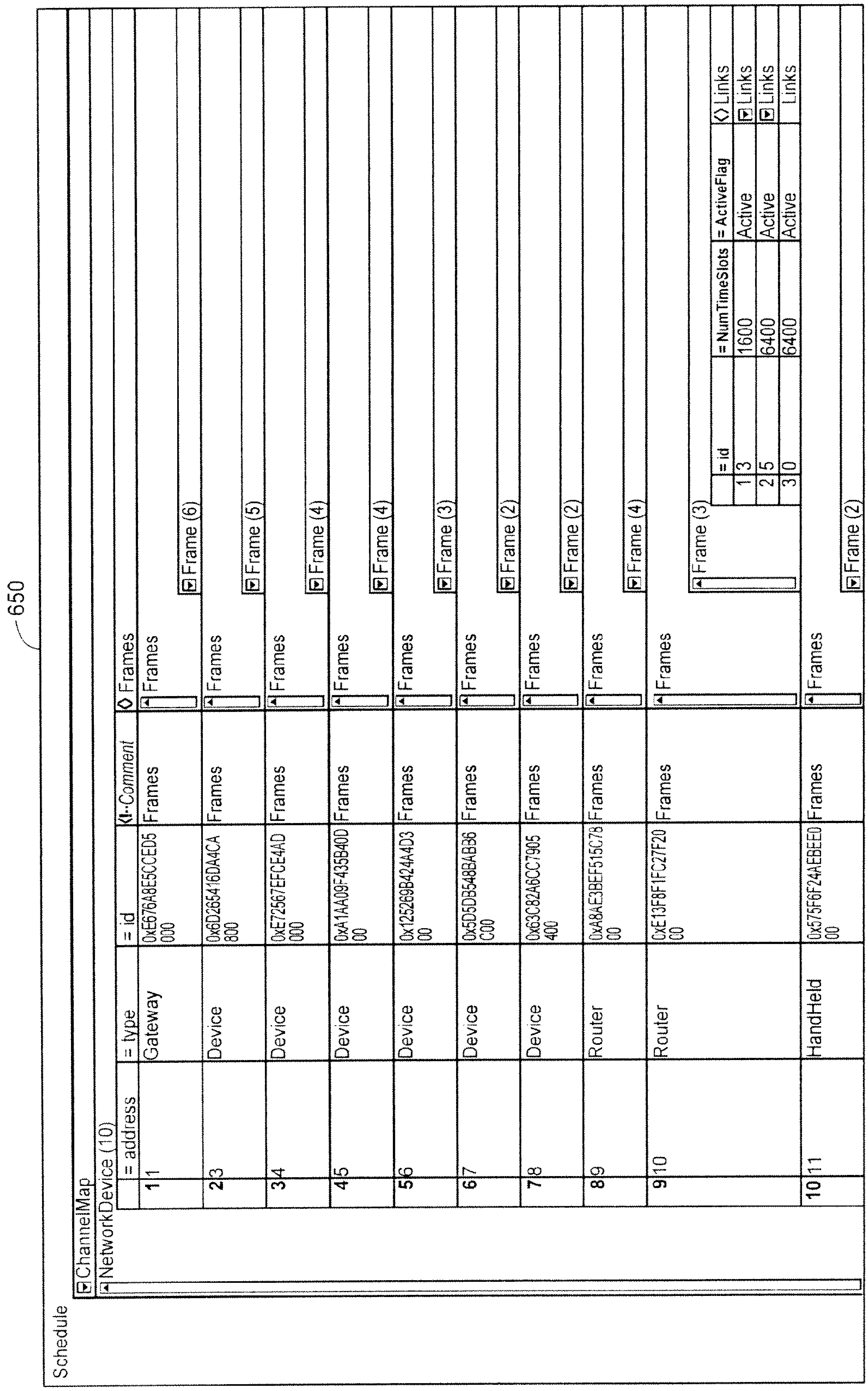

650
Schedule
ChannelMap
NetworkDevice (10)
= address
= type
= id
Comment
Frames
1 1 Gateway 0xE676A8E5CCED5000 Frames Frames Frame (6)
2 3 Device 0x6D265416DA4CA800 Frames Frames Frame (5)
3 4 Device 0xE72567EFCE4AD000 Frames Frames Frame (4)
4 5 Device 0xA1AA09F435B40D00 Frames Frames Frame (4)
5 6 Device 0x125269B424A4D300 Frames Frames Frame (3)
6 7 Device 0x5D5DB548BAB36C00 Frames Frames Frame (2)
7 8 Device 0x63C82A6CC7905400 Frames Frames Frame (2)
8 9 Router 0xA8AE3BEF515C7800 Frames Frames Frame (4)
9 10 Router 0xE13F8F1FC27F2000 Frames Frames Frame (3)
= id
= NumTimeSlots
= ActiveFlag
Links
1 3 1600 Active Links
2 5 6400 Active Links
3 0 6400 Active Links
10 11 HandHeld 0x575F6F24AEBEE000 Frames Frames Frame (2)

FIG. 16A

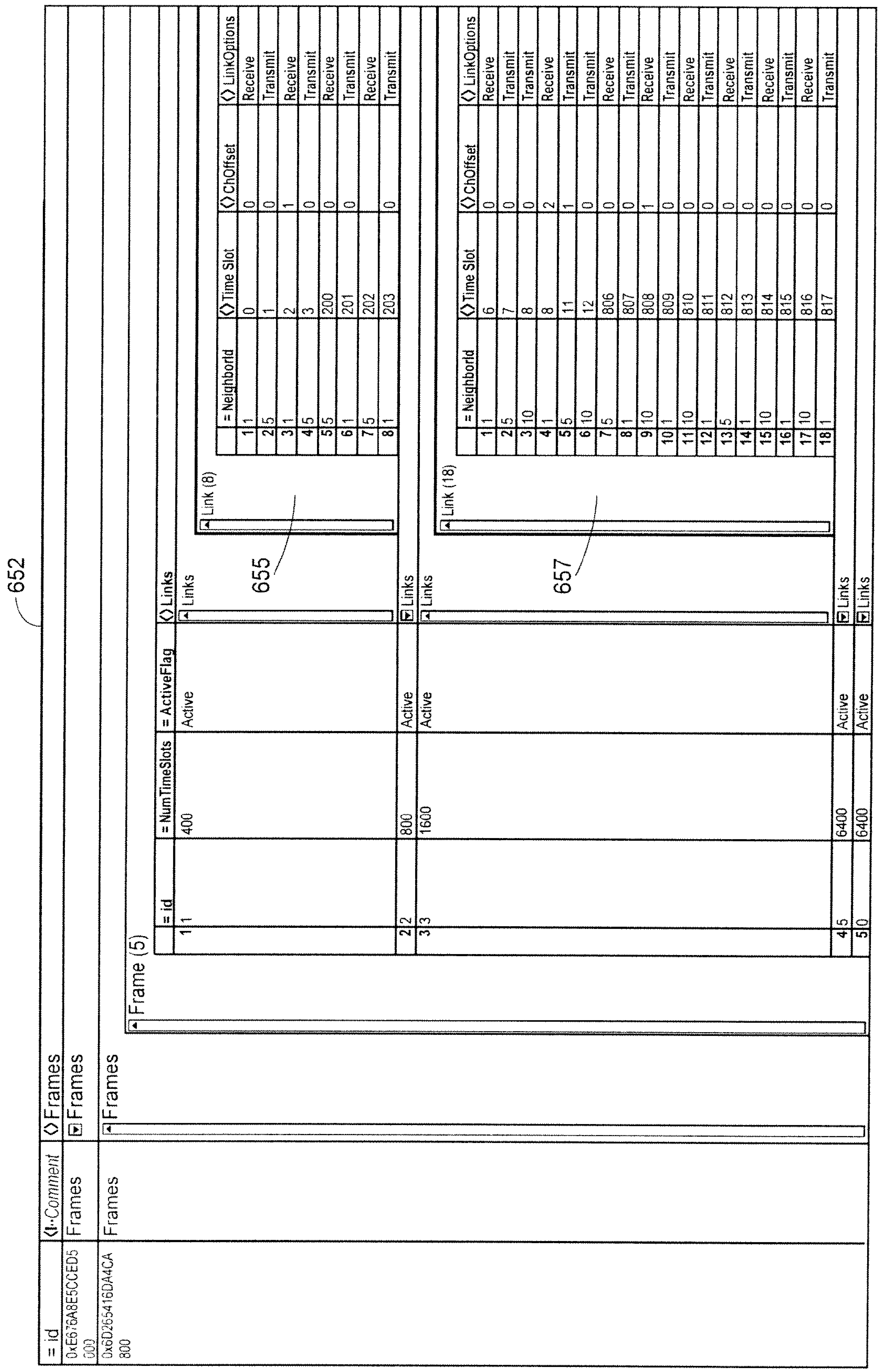

652
= id
Comment
Frames
0xE676A8E5CCED5 009
0x6D265416DA4CA 800
Frame (5)
= id
= NumTimeSlots
= ActiveFlag
Links
1 1 400 Active
2 2 800 Active
3 3 1600 Active
4 5 6400 Active
5 0 6400 Active
Link (8)
655
= NeighborId
Time Slot
ChOffset
LinkOptions
1 1 0 0 Receive
2 5 1 0 Transmit
3 1 2 1 Receive
4 5 3 0 Transmit
5 5 200 0 Receive
6 1 201 0 Transmit
7 5 202 Receive
8 1 203 0 Transmit
Link (18)
657
1 1 6 0 Receive
2 5 7 0 Transmit
3 10 8 0 Transmit
4 1 8 2 Receive
5 5 11 1 Transmit
6 10 12 0 Transmit
7 5 806 0 Receive
8 1 807 0 Transmit
9 10 808 1 Receive
10 1 809 0 Transmit
11 10 810 0 Receive
12 1 811 0 Transmit
13 5 812 0 Receive
14 1 813 0 Transmit
15 10 814 0 Receive
16 1 815 0 Transmit
17 10 816 0 Receive
18 1 817 0 Transmit

FIG. 16B

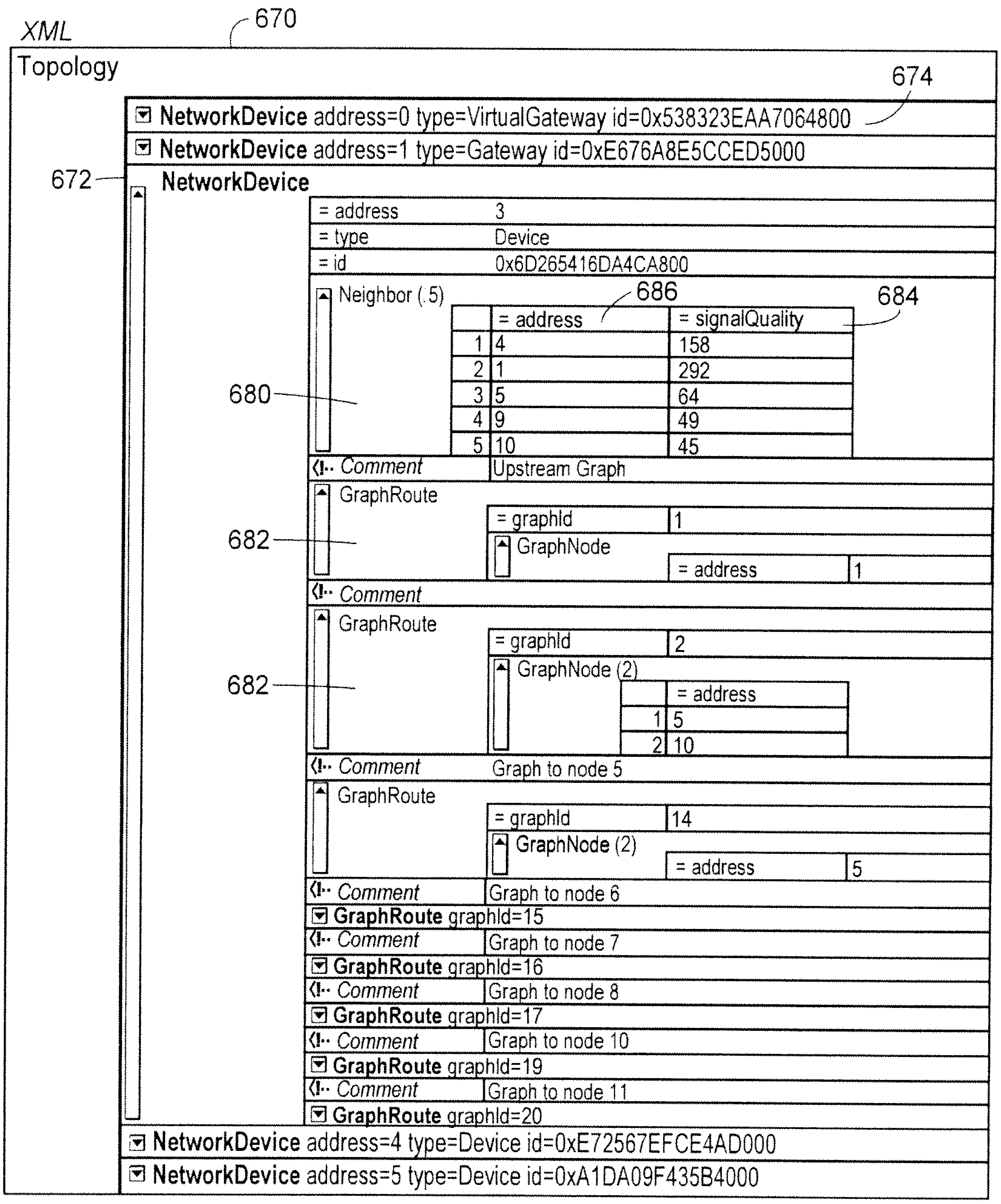

XML
670
Topology
674
NetworkDevice address=0 type=VirtualGateway id=0x538323EAA7064800
NetworkDevice address=1 type=Gateway id=0xE676A8E5CCED5000
672
NetworkDevice
= address 3
= type Device
= id 0x6D265416DA4CA800
Neighbor (5)
686
684
= address
= signalQuality
1 4 158
2 1 292
3 5 64
4 9 49
5 10 45
680
Comment Upstream Graph
GraphRoute
682
= graphId 1
GraphNode
= address 1
Comment
GraphRoute
682
= graphId 2
GraphNode (2)
= address
1 5
2 10
Comment Graph to node 5
GraphRoute
= graphId 14
GraphNode (2)
= address 5
Comment Graph to node 6
GraphRoute graphId=15
Comment Graph to node 7
GraphRoute graphId=16
Comment Graph to node 8
GraphRoute graphId=17
Comment Graph to node 10
GraphRoute graphId=19
Comment Graph to node 11
GraphRoute graphId=20
NetworkDevice address=4 type=Device id=0xE72567EFCE4AD000
NetworkDevice address=5 type=Device id=0xA1DA09F435B4000

FIG. 17

CONFIGURING AND OPTIMIZING A WIRELESS MESH NETWORK

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent App. No. 60/969,420 entitled "Configuring and Optimizing a Wireless Mesh Network," filed Aug. 31, 2007, the disclosure of which is hereby expressly incorporated herein by reference.

FIELD OF TECHNOLOGY

The present invention relates generally to managing wireless networks and, more particularly, to a method of configuring and optimizing a wireless mesh network by means of an interactive user interface and automated optimization routines.

BACKGROUND TECHNOLOGY

Communication protocols rely on various routing techniques to transfer data between communication endpoints on a communication network. Communication or network protocols and the corresponding routing strategies are typically selected in view of such factors as knowledge of network topology, size of the network, type of medium used as a signal carrier, security and reliability requirements, tolerable transmission delays, and types of devices forming the network. Due to a large number of such factors, a typical routing technique meets some of the design objectives at the expense of the others. For example, a certain routing technique may provide a high level of reliability in data delivery but may also require a relatively high overhead. Thus, while there are many known approaches to routing and many protocols compatible with these routing methods, there remain communication networks with the specific requirements that are not fully satisfied by any of the available routing methods and protocols. Moreover, as new types of communication networks, with the increasing demands for efficiency, throughput, and reliability, emerge in various industrial and commercial applications, the architects and developers frequently encounter new problems which are not easily addressed by the existing protocols and the associated routing techniques.

Generally speaking, a communication network includes nodes which are the senders and recipients of data and communication paths connecting the nodes. Additionally, communication networks typically include dedicated routers responsible for directing traffic between nodes, and, optionally, dedicated devices responsible for configuring and managing the network. Some or all of the nodes may be also adapted to function as routers in order to direct traffic sent between other network devices. Network devices may be inter-connected in a wired or wireless manner, and network devices may have different routing and transfer capabilities. For example, dedicated routers may be capable of high volume transmissions while some nodes may be capable of sending and receiving relatively little traffic over the same period of time. Additionally, the connections between nodes on a network may have different throughput capabilities and different attenuation characteristics. A fiberoptic cable, for example, may be capable of providing a bandwidth several orders of magnitude higher than a wireless link because of the difference in the inherent physical limitations of the medium.

In order for a node to send data to another node on a typical network, either the complete path from the source to the destination or the immediately relevant part of the path must be known. For example, the World Wide Web (WWW) allows pairs of computer hosts to communicate over large distances without either host knowing the complete path prior to sending the information. Instead, hosts are configured with the information about their assigned gateways and dedicated routers. In particular, the Internet Protocol (IP) provides network layer connectivity to the WWW. IP defines a sub-protocol known as Address Resolution Protocol (ARP) which provides a local table at each host specifying the routing rules. Thus, a typical host connected to the WWW or a similar Wide Area Network (WAN) may know to route all packets with the predefined addresses matching a pre-configured pattern to host A and route the rest of the packets to host B. Similarly, the intermediate hosts forwarding the packets, or "hops," also execute partial routing decisions and typically direct data in the general direction of the destination.

Routing strategies on a typical network may be further complicated by scheduling issues. In general, scheduling refers to allocation of resources, such as timeslots on a wired or wireless link, to devices participating in communications on a network. Selecting a proper scheduling strategy and generating the optimal schedule for a particular network may be particularly relevant in a wireless environment. Because the number of available frequencies is typically limited, network hosts may not be able to transmit or receive data as soon as this data becomes available. For example, a pair of communicating devices, each capable of operating in receive and transmit modes, may exchange data over a single carrier frequency. In order to resolve potential collisions during transmissions and prevent the devices from missing data by failing to enter the receive mode at the right time, one could define a schedule assigning some transmission opportunities to the first device and the rest of the transmission opportunities to the second device. By complying with the schedule, the pair of devices could successfully maintain bidirectional data exchange over the same carrier frequency.

Unlike the example discussed above, most wireless networks include numerous devices and each device may have idiosyncratic requirements with respect to the amount of data the device needs to transmit, the rates of transmission and reception, the maximum amount of data the device is capable of receiving and transmitting per unit of time, the tolerable latency and potentially many other factors. Thus, scheduling decisions may become very complex and optimizing scheduling may become a high priority in many applications. Moreover, routing decisions and scheduling decisions may have a significant impact on each other and, as a result, may require an even more complicated simultaneous definition and optimization.

In short, there is a large number of factors influencing the implementation of particular protocols in particular industries. In the process control industry, it is known to use standardized communication protocols to enable devices made by different manufacturers to communicate with one another in an easy to use and easy to implement manner. One such well known communication standard used in the process control industry is the Highway Addressable Remote Transmitter (HART) Communication Foundation protocol, referred to generally as the HART protocol. Generally speaking, the HART protocol supports a combined digital and analog signal on a dedicated wire or set of wires, in which on-line process signals (such as control signals, sensor measurements, etc.) are provided as an analog current signal (e.g., ranging from 4 to 20 milliamps) and other signals, such as device data, requests for device data, configuration data, alarm and event data, etc., are provided as digital signals superimposed or multiplexed onto the same wire or set of wires as the analog signal. However, the HART protocol currently requires the use of dedicated, hardwired communication lines, resulting in significant wiring needs within a process plant.

There has been a move, in the past number of years, to incorporate wireless technology into various industries including, in some limited manners, the process control industry. However, there are significant hurdles in the process control industry that limit the full scale incorporation, acceptance and use of wireless technology, as the process control industry requires a completely reliable process control network because loss of signals can result in the loss of control of a plant, leading to catastrophic consequences, including explosions, the release of deadly chemicals or gases, etc. For example, Tapperson et al., U.S. Pat. No. 6,236,334 discloses the use of a wireless communications in the process control industry as a secondary or backup communication path or for use in sending non-critical or redundant communication signals. Moreover, there have been many advances in the use of wireless communication systems in general that may be applicable to the process control industry, but which have not yet been applied to the process control industry in a manner that allows or provides a reliable, and in some instances completely wireless, communication network within a process plant. U.S. Patent Application Publication Numbers 2005/0213612, 2006/0029060 and 2006/0029061 for example disclose various aspects of wireless communication technology related to a general wireless communication system.

Similar to wired communications, wireless communication protocols are expected to provide efficient, reliable and secure methods of exchanging information. Of course, much of the methodology developed to address these concerns on wired networks does not apply to wireless communications because of the shared and open nature of the medium. Further, in addition to the typical objectives behind a wired communication protocol, wireless protocols face other requirements with respect to the issues of interference and co-existence of several networks that use the same part of the radio frequency spectrum. Moreover, some wireless networks operate in the part of the spectrum that is unlicensed, or open to the public. Therefore, protocols servicing such networks must be capable of detecting and resolving issues related to frequency (channel) contention, radio resource sharing and negotiation, etc.

In order to properly configure a wireless network, engineers and maintenance personnel must consider a large number of factors. In particular, engineers must evaluate at least the topology of the network and the capacity of network connections. Moreover, many applications in the process control industry, to take one example, require a degree of reliability, security, and efficiency which is significantly higher than the standards applied to most commercial or household applications. In order to meet these additional requirements, process control engineers must optimize both routing and scheduling in the wireless network. In other words, engineers must simultaneously pursue several design objectives, such as reducing latency, increasing reliability, and minimizing cost. Some of these objectives may not be compatible with each other at all times and the engineers may have to make difficult trade-off decisions. In cases when large plants have process control networks including many devices of different types, efficiently designing a wireless network may become even more time-consuming and challenging. Meanwhile, even minor mistakes in configuration may noticeably reduce the efficiency of a plant in which a wireless process control network is implemented and thus cause operators to incur significant financial losses.

Further, new facts or design considerations may become apparent only during the operation of a wireless network. For this reason, engineers may require a certain amount of testing prior to deployment. One or more tests may generate new data, parameters, and measurements which must then be incorporated into the existing design and, in particular, into the previously developed routes and schedules. Efficiently applying test data to an existing configuration without re-designing the entire network may become a challenging technical issue comparable to the difficulty of creating the original design.

Still further, network nodes may be added, removed, or repositioned in an existing wireless network, thereby rendering some of the routing and scheduling schemes ineffective or deficient. To continue with the example of the process control industry, a change in a network layout may require a new network configuration and a possible shutdown of a plant for the duration of configuration and testing.

SUMMARY

An interactive software tool for wireless network design allows a user to create a model of a wireless network, input several design requirements, and automatically generate routes and schedules for the network. The network design tool provides interactive graphic interface for the addition, removal, and positioning of nodes of the wireless network. Additionally, the network design tool provides a user menu including several interactive screens for specifying threshold values, network topology selections, routing preferences, and other configuration parameters related to generating routes and schedules. The network design tool automatically applies a set of optimization rules along with the parameters input by user to the network model in order to generate an efficient network schedule and identify routing paths, thereby optimizing the performance of the network. The network design tool is capable of displaying the generated schedules graphically, textually, or in an XML format. In one embodiment, the network design tool adjusts paths and schedules every time user makes changes to the network model or to the configuration parameters. The network design tool simulates the operation of the wireless network corresponding to the network model and provides feedback to the user in form of graphical indicators, text, and possibly sound.

In one aspect, the network design tool graphically depicts the network model using a set of predefined shapes and colors. In one embodiment, each network node is illustrated as a circle and each connection between a pair of nodes is illustrated as a line. In some embodiments, the lines include unidirectional or bidirectional arrows in order to indicate the direction of traffic in the simulated network. Additionally, the line color indicates whether the connection is potential or actual. In some embodiments, the circles representing network nodes additionally include symbols indicating a network device type and are colored according to the status of the network device. Several auxiliary symbols may provide such additional information as the energy source of a network device, signal attenuation at a particular location, and other facts helpful in viewing and operating a model of a wireless network.

In another aspect, the network design tool is communicatively coupled to the actual plant or automation network corresponding to the network model. The actual plant provides feedback to the network design tool in form of signal strength measurements, delay measurements, and other parameters useful in evaluating the performance of the network. The network design tool applies this live data to the network model and corrects, when necessary, the routing and scheduling decisions.

In yet another aspect, the optimization rules applied to the network model include such principles as minimizing the number of intermediate nodes, or "hops," between pairs of communicating devices, preferring routing through those devices which have a more reliable power source, and avoiding node overload. In another aspect, the optimization rules are ranked in importance for conflict resolution, with a higher ranking rule taking precedence over a lower ranking rule whenever the two rules are not compatible in application to a certain scheduling or routing decision. In another aspect, some of the optimization rules are directed to optimizing the power consumption of the wireless network and extending battery lives of battery-powered devices by routing data through devices with constant power sources whenever possible.

In another aspect, the network design tool accounts for the particulars of a wireless HART network and differentiates between such wireless HART network device types as gateway, network access point, router, and field device. The user may select the shapes or symbols corresponding to each wireless HART device type from the menu or from a toolbar provided as part of the user interface. Additionally, the network design tool allows the user to configure burst rates, or frequency of reporting process data to a Distributed Control System (DCS) or similar control unit, for each field device. Moreover, the network design tool automatically places one or more gateway devices at the head of a master graph corresponding to the collection of routing paths in the wireless network. The network design tool then defines, simulates, and adjusts routing of data both upstream and downstream with respect to head of the graph. In this aspect, the network design tool optimizes a wireless network for use in a process control environment supporting the wireless extension of the HART protocol.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram that illustrates a system utilizing a wireless HART network to provide wireless communication between field and router devices, which are connected to a plant automation network via a gateway device.

FIG. **2** is a schematic representation of the layers of a wireless HART protocol implemented in accordance with one of the embodiments discussed herein.

FIG. **3** is a block diagram illustrating the use of wireless HART devices with a tank farm.

FIG. **4** schematically illustrates a star network topology.

FIG. **5** schematically illustrates a mesh network topology.

FIG. **6** schematically illustrates a star mesh network topology.

FIG. **7** is a block diagram illustrating path redundancy provided by a wireless HART protocol.

FIG. **8** is a block diagram schematically illustrating an exemplary software architecture of a network design tool to be used with a wireless communication network.

FIG. **9** is a block diagram illustrating an exemplary menu of a network design tool of FIG. **8**.

FIG. **10** is an exemplary screen of the network design tool illustrating creation of a network model.

FIG. **11** is another exemplary screen of the network design tool illustrating rule and preference configuration for generating network graphs.

FIG. **11**A illustrates a flow chart of a general exemplary algorithm which the network design tool may execute during automatic graph definition.

FIG. **12** is a screen of the network design tool illustrating an automatic update to the network graph triggered by a change in a threshold signal strength.

FIG. **13** is another exemplary screen of the network design tool illustrating obstacle simulation.

FIG. **14** is a screen of the network design tool illustrating an automatic update to the network graph triggered by a change in the location of the obstacle.

FIG. **14**A illustrates an exemplary scheduling procedure responsible for design constraint enforcement which may be executed by the network design tool.

FIG. **14**B illustrates an exemplary scheduling procedure responsible for data superframe configuration which may be executed by the network design tool.

FIG. **14**C illustrates an exemplary scheduling procedure responsible for management superframe configuration which may be executed by the network design tool.

FIG. **15** is an exemplary screen of the network design tool graphically illustrating time slot allocation, assignment, and other scheduling parameters.

FIG. **16**A is an exemplary screen of the network design tool textually specifying time slot allocation, assignment, and other scheduling parameters.

FIG. **16**B is another exemplary screen of the network design tool displaying an expanded view of several parameters of one of the devices listed in the exemplary screen of FIG. **16**A.

FIG. **17** an exemplary screen of the network design tool textually specifying graph routing parameters.

DETAILED DESCRIPTION

FIG. **1** illustrates an exemplary network **10** to which a network design tool described herein may be applied or with which the network design and optimization tool may be used. In particular, the network **10** may include a plant automation network **12** and a wireless HART network **14**. The plant automation network **12** may include one or more stationary workstations **16** and one or more portable workstations **18** connected over a communication backbone **20**. The backbone **20** may be implemented over Ethernet, RS-485, Profibus DP or other suitable communication protocol. The plant automation network **12** and the wireless HART network **14** may be connected via a gateway **22**. Specifically, the gateway **22** may be connected to the backbone **20** in a wired manner and may communicate with the plant automation network **12** by using any suitable known protocol. The gateway **22** may be implemented as a standalone device, as a card insertable into an expansion slot of the hosts or workstations **16** or **18**, or as part of the IO subsystem of a PLC-based or DCS-based system, or in any other manner. The gateway **22** provides applications running on the network **12** access to various devices of the wireless HART network **14**. In addition to protocol and command conversion, the gateway **22** may provide synchronized clocking used by time slots and superframes (sets of communication time slots spaced equally in time) of the scheduling scheme of the wireless HART network **14**.

In some situations, networks may have more than one gateway **22**. These multiple gateways can be used to improve the effective throughput and reliability of the network by providing additional bandwidth for the communication between the wireless HART network and the plant automation network **12** or the outside world. On the other hand, the gateway **22** device may request bandwidth from the appropriate network service according to the gateway communication needs within the wireless HART network. The gateway **22** may further reassess the necessary bandwidth while the system is operational. For example, the gateway **22** may receive a request from a host residing outside the wireless HART network **14** to retrieve a large amount of data. The gateway device **22** may then request additional bandwidth from a dedicated service such as a network manager in order to accommodate this transaction. The gateway **22** may then request the release of the unnecessary bandwidth upon completion of the transaction.

In some embodiments, the gateway **22** is functionally divided into a virtual gateway **24** and one or more network access points **25**. Network access points **25** may be separate physical devices in wired communication with the gateway **22** in order to increase the bandwidth and the overall reliability of the wireless HART network **14**. However, while FIG. **1** illustrates a wired connection **26** between the physically separate gateway **22** and access points **25**, it will be understood that the elements **22-26** may also be provided as an integral device. Because network access points **25** may be physically separate from the gateway device **22**, the access points **25** may be strategically placed in several distinct locations. In addition to increasing the bandwidth, multiple access points **25** can increase the overall reliability of the network by compensating for a potentially poor signal quality at one access point at one or more other access points. Having multiple access points **25** also provides redundancy in case of failure at one or more of the access points **25**.

The gateway device **22** may additionally contain a network manager software module **27** and a security manager software module **28**. In another embodiment, the network manager **27** and/or the security manager **28** may run on one of the hosts on the plant automation network **12**. For example, the network manager **27** may run on the host **16** and the security manager **28** may run on the host **18**. The network manager **27** may be responsible for configuration of the network, scheduling communication between wireless HART devices (i.e., configuring superframes), management of the routing tables and monitoring and reporting the health of the wireless HART network **14**. While redundant network managers **27** are supported, it is contemplated that there should be only one active network manager **27** per wireless HART network **14**.

Referring again to FIG. **1**, the wireless HART network **14** may include one or more field devices **30-40**. In general, process control systems, like those used in chemical, petroleum or other process plants, include such field devices as valves, valve positioners, switches, sensors (e.g., temperature, pressure and flow rate sensors), pumps, fans, etc. Field devices perform control functions within the process such as opening or closing valves and taking measurements of process parameters. In the wireless HART communication network **14**, field devices **30-40** are producers and consumers of wireless HART packets.

An external host **41** may be connected to a network **43** which, in turn, may be connected to the plant automation network **12** via a router **44**. The network **43** may be, for example, the World Wide Web (WWW). Although the external host **41** does not belong to either the plant automation network **12** or the wireless HART network **14**, the external host **41** may access devices on both networks via the router **44**. A network design tool **45** may reside and run on the external host **41** and provide the wireless network configuration and simulation functionality discussed in greater detail below. Alternatively, the network design tool **45** may run on the stationary workstation **16**, on the portable workstation **18**, or on a portable device connected directly to the wireless HART network **14**. In some embodiments, the network design tool **45** may run in a distributed manner on several hosts of the network **10**. In yet another embodiment, the network design tool **45** may run on a standalone host **47** and therefore have no access or only periodic access to either the network **12** or the network **14**. In this case, the feedback information related to the performance of the wireless network **14** may be entered manually into the network design tool **45** by means of the host **47**.

The network design tool **45** may be implemented as a software package using one or more programming languages such as C/C++ or JAVA, or for example. The software of the network design tool **45** may be stored on one or several hosts **16**, **18**, **41**, or **47** in a conventional manner. Alternatively, the network design tool **45** may be provided on a portable memory disk such as a CD or DVD and may be loaded into the volatile memory of a computer host during operation. For example, some or all of the hosts **16**, **18**, **41**, and **47** may include hard drives and flash drives capable of permanently storing software and CD and DVD drives compatible with a CD or DVD containing the network design tool **45**. In another embodiment, the network design tool **45** may be provided as a distributed web service, or a software running remotely and accessible via the internet or intranet. For example, the remote host **41** may contain some of the software components of the network design tool **45** while the workstation **16** may provide user interface to operators via a keyboard, a mouse, a computer screen, and similar input/output devices. In accordance with this embodiment, operators may access and benefit from some or all of the features of the network design tool **45** but the software of the network design tool **45** may reside remotely for security or copyright reasons.

The wireless HART network **14** may use a protocol which provides similar operational performance that is experienced with wired HART devices. The applications of this protocol may include process data monitoring, critical data monitoring (with the more stringent performance requirements), calibration, device status and diagnostic monitoring, field device troubleshooting, commissioning, and supervisory process control. These applications require that the wireless HART network **14** use a protocol which can provide fast updates when necessary, move large amounts of data when required, and support network devices which join the wireless HART network **14** only temporarily for commissioning and maintenance work.

In one embodiment, the wireless protocol supporting network devices of the wireless HART network **14** is an extension of HART, a widely accepted industry standard, that maintains the simple workflow and practices of the wired environment. In accordance with this embodiment, the same tools used for wired HART devices may be easily adapted to wireless devices with the simple addition of new device description files. In this manner, the wireless HART protocol leverages the experience and knowledge gained using HART to minimize training and simplify maintenance and support. Generally speaking, it may be convenient to adapt a protocol for wireless use so that most applications running on a device do not "notice" the transition from a wired network to a wireless network. Clearly, such transparency greatly reduces the cost of upgrading networks and, more generally, developing and supporting devices that may be used with such networks. Some of the additional benefits of a wireless extension of HART include: access to measurements that were difficult or expensive to get to with wired devices, ability to configure and operate instruments from system software that can be installed on laptops, handhelds, workstations, etc. Another benefit is the ability to send diagnostic alerts from wireless devices back through the various communication techniques to a centrally located diagnostic center. For example, every heat exchanger could be fitted with a wireless HART device and the end user and supplier alerted when the heat exchanger detects a problem. Yet another benefit is the ability to monitor conditions that present serious health and safety problems. For example, a wireless HART device could be placed in flood zones on roads and used to alert authorities and drivers about water levels. Other benefits include access to wide range of diagnostics alerts and the ability to store trended as well as calculated values at the wireless HART device so that when communications to the device are established the values can be transferred to the host. Thus, a wireless HART protocol can provide technology for host applications to have wireless access to existing HART-enabled field devices and will support the deployment of battery operated, wireless only HART-enabled field devices. The wireless HART protocol may be used to establish a wireless communication standard for process applications and may further extend the application of HART communications and the benefits it provides to industry by enhancing the HART technology to support wireless process automation applications.

Referring again to FIG. **1**, field devices **30-36** may be wireless HART devices. In other words, a field device **30**, **32**, **34**, or **36** may be provided as an integral unit supporting all layers of the wireless HART protocol stack. In the network **10**, the field device **30** may be a wireless HART flow meter, the field devices **32** may be wireless HART pressure sensors, the field device **34** may be a wireless HART valve positioner, and the field device **36** may a wireless HART pressure sensor. Importantly, wireless HART devices **30-36** are HART devices supporting all that users have come to expect from the wired HART protocol. As one of ordinary skill in the art will appreciate, one of the core strengths of the HART protocol is its rigorous interoperability requirements. In some embodiments, all wireless HART equipment includes core mandatory capabilities in order to allow equivalent device types to be exchanged without compromising system operation. Furthermore, the wireless HART protocol is backward compatible to HART core technology such as the device description language (DDL). In the preferred embodiment, all HART devices should support the DDL, which ensures that end users immediately have the tools to begin utilizing the wireless HART protocol.

On the other hand, a field device **38** may be a legacy 4-20 mA device and a field device **40** may be a wired HART device. Field devices **38** and **40** may be connected to the wireless HART network **13** via a wireless HART adaptor (WHA) **50**. Additionally, the WHA **50** may support other communication protocols such as Foundation Fieldbus, PROFIBUS, DevicesNet, etc. In these embodiments, the WHA **50** supports protocol translation on a lower layer of the protocol stack. Additionally, it is contemplated that a single WHA **50** may also function as a multiplexer and support multiple HART or non-HART devices.

Plant personnel may additionally use handheld devices for installation, control, monitoring, and maintenance of network devices. Generally speaking, handheld devices are portable equipment that can connect directly to the wireless HART network **14** or through the gateway **22** as a host on the plant automation network **12**. As illustrated in FIG. **1**, a wireless HART-connected handheld device **55** communicates directly to the wireless HART network **14**. When operating with a formed wireless HART network **14**, this device may join the network **14** as just another wireless HART field device. When operating with a target network device that is not connected to a wireless HART network, the handheld device **55** may operate as a combination of the gateway device **22** and the network manager **27** by forming its own wireless HART network with the target network device.

A plant automation network-connected handheld device (not shown) connects to the plant automation network **12** through known networking technology, such as Wi-Fi. This device talks to the network devices **30-40** through the gateway device **22** in the same fashion as external plant automation servers (not shown) or the workstations **16** and **18**.

Additionally, the wireless HART network **14** may include a router device **60**. The router device **60** is a network device that forwards packets from one network device to another. A network device that is acting as a router device uses internal routing tables to decide to which network device it should forward a particular packet. Stand alone routers such as the router **60** may not be required in those embodiments where all devices on the wireless HART network **14** support routing. However, it may be beneficial (e.g. to extend the network, or to save the power of a field device in the network) to add a dedicated router **60** to the network.

All devices directly connected to the wireless HART network **14** may be referred to as network devices. In particular, the wireless HART field devices **30-36**, the adaptors **50**, the routers **60**, the gateway **22**, the access points **25**, and the wireless HART-connected handheld device **55** are, for the purposes of routing and scheduling, the network devices or the nodes of the wireless HART network **14**. In order to provide a very robust and an easily expandable network, it is contemplated that all network devices may support routing and each network device may be globally identified by its HART address. The network manager **27** may contain a complete list of network devices and assign each device a short, network unique 16-bit nickname. Additionally, each network device may store information related to update rates, connections sessions, and device resources. In short, each network device maintains up-to-date information related to routing and scheduling. The network manager **27** communicates this information to network devices whenever new devices join the network or whenever the network manager detects or originates a change in topology or scheduling of the wireless HART network **14**.

Further, each network device may store and maintain a list of neighbor devices that the network device has identified during the listening operations. Generally speaking, a neighbor of a network device is another network device of any type potentially capable of establishing a connection with the network device in accordance with the standards imposed by a corresponding network. In case of the wireless HART network **14**, the connection is a wireless connection. However, it will be appreciated that a neighboring device may also be a network device connected to the particular device in a wired manner. As will be discussed later, network devices promote their discovery by other network devices through advertisement, or special messages sent out during the designated timeslots. Network devices operatively connected to the wireless HART network **14** have one or more neighbors which they may choose according to the strength of the advertising signal or to some other principle. Referring again to FIG. **1**, in a pair of network devices connected by a direct wireless connection **65**, each device recognizes the other as a neighbor. Thus, network devices of the wireless HART network **14** may form a large number of connections **65**. The possibility and desirability of establishing a direct wireless connection **65** between two network devices is determined by several factors such as the physical distance between the nodes, obstacles between the nodes, signal strength at each of the two nodes, etc. Further, two or more direct wireless connections **65** may form paths between nodes that cannot form a direct wireless connection **65**. For example, the direct wireless connection **65** between the wireless HART hand-held device **55** and wireless HART device **36** along with the second direct wireless connection **65** between the wireless HART device **36** the router **60** form a communication path between devices **55** and **60**.

Each wireless connection **65** is characterized by a large set of parameters related to the frequency of transmission, the method of access to the radio resource, etc. One of ordinary skill in the art will recognize that, in general, wireless communication protocols may operate on designated frequencies, such as the ones assigned by the Federal Communications Commission (FCC) in the United States, or in the unlicensed part of the radio spectrum (2.4 GHz). While the system and method discussed herein may be applied to a wireless network operating on any designated frequency or range of frequencies, the embodiment discussed below relates to the wireless HART network **14** operating in the unlicensed, or shared part of the radio spectrum. In accordance with this embodiment, the wireless HART network **14** may be easily activated and adjusted to operate in a particular unlicensed frequency range as needed.

For a wireless network protocol using an unlicensed frequency band, coexistence is a core requirement because a wide variety of communication equipment and interference sources may be present. Thus, in order to successfully communicate, devices using a wireless protocol must coexist with other equipment utilizing this band. Coexistence generally defines the ability of one system to perform a task in a given shared environment in which other systems have an ability to perform their tasks, wherein the various systems may or may not be using the same set of rules. One requirement of coexistence in a wireless environment is the ability of the protocol to maintain communication while there is interference present in the environment. Another requirement is that the protocol should cause as little interference and disruption as possible with respect to other communication systems.

In other words, the problem of coexistence of a wireless system with the surrounding wireless environment has two general aspects. The first aspect of coexistence is the manner in which the system affects other systems. For example, an operator or developer of the system may ask what impact the transmitted signal of one transmitter has on other radio systems operating in proximity to the system. More specifically, the operator may ask whether the transmitter disrupts communication of some other wireless device every time the transmitter turns on or whether the transmitter spends excessive time on the air effectively "hogging" the bandwidth. One familiar with wireless communications will agree that ideally, each transmitter should be a "silent neighbor" that no other transmitter notices. While these ideal characteristics are rarely, if ever, attainable, a wireless system that creates a coexistence environment in which other wireless communication systems may operate reasonably well may be called a "good neighbor." The second aspect of coexistence of a wireless system is the ability of the system to operate reasonably well while other systems or wireless signal sources are present. In particular, the robustness of the system may depend on how well the system prevents interference at the receivers, on whether the receivers easily overload due to proximate sources of RF energy, on how well the receivers tolerate an occasional bit loss, and similar factors. In some industries, including the process control industry, there is a number of important potential applications of a wireless communication system. In these applications, loss of data is frequently not allowable. A wireless system capable of providing reliable communications in a noisy or dynamic radio environment may be called a "tolerant neighbor."

Coexistence relies (in part) on effectively employing three aspects of freedom: time, frequency and distance. Communication can be successful when it occurs at a 1) time when the interference source (or other communication system) is quiet; 2) different frequency than the interference; or 3) location sufficiently removed from the interference source. While a single one of these factors could be used to provide a communication scheme in the shared part of the radio spectrum, taking into account a combination of two or all three of these factors can provide a high degree of reliability, security and speed.

In one embodiment, the protocol supporting the wireless HART network **14** is a wireless HART protocol **70**. More specifically, each of the direct wireless connections **65** may transfer data according to the physical and logical requirements of the wireless HART protocol **70**. FIG. **2** schematically illustrates the structure of one of the embodiments of the protocol **70** and of the existing "wired" HART protocol **72**. The wireless HART protocol **70** may be a secure, wireless mesh networking technology operating in the 2.4 GHz ISM radio band (block **74**). In one embodiment, the wireless HART protocol **70** may utilize IEEE 802.15.4b compatible direct sequence spread spectrum (DSSS) radios with channel hopping on a transaction by transaction basis. This wireless HART communication may be arbitrated using time division multiple access or Time Division Multiple Access (TDMA) to schedule link activity (block **76**). All communications are preferably performed within a designated time slot. One or more source and one or more destination devices may be scheduled to communicate in a given slot, and each slot may be dedicated to communication from a single source device or to a CSMA/CA-like shared communication access mode between multiple source devices. Source devices may send messages to specific target device or broadcast messages to all of the destination devices assigned to the slot.

To enhance reliability, the wireless HART protocol **70** may combine TDMA with a method of associating multiple radio frequencies with a single communication resource, or channel hopping. Channel hopping provides frequency diversity which minimizes interference and reduces multi-path fading effects. In particular, the data link **76** may create an association between a single superframe and multiple carrier frequencies which the data link **76** cycles through in a controlled predefined manner. For example, the available frequency band of a particular instance of the wireless HART network **14** may have carrier frequencies F_1, F_2, . . . F_n. A relative frame R of a superframe S may be scheduled to occur at a frequency F_1 in the cycle C_n, at a frequency F_5

in the following cycle C_{n+1}, at a frequency F_2 in the cycle C_{n+2}, and so on. The network manager **27** may configure the relevant network devices with this information so that the network devices communicating in the superframe S may adjust the frequency of transmission or reception according to the current cycle of the superframe S.

The data link **76** of the wireless HART protocol **70** may offer an additional feature of channel blacklisting, or restricting the use of certain channels in the radio band by the network devices. The network manager **27** may blacklist a radio channel in response to detecting excessive interference or other problems on the channel. Further, operators or network administrators may blacklist channels in order to protect a wireless service that uses a fixed portion of the radio band that would otherwise be shared with the wireless HART network **14**. In some embodiments, the wireless HART protocol **70** controls blacklisting on a superframe basis so that each superframe has a separate blacklist of prohibited channels.

In one embodiment, the network manager **27** is responsible for allocating, assigning, and adjusting time slot resources associated with the data link layer **76**. If a single instance of the network manager **27** supports multiple wireless HART networks **14**, the network manager **27** may create an overall schedule for each instance of the wireless HART network **14**. The schedule may be organized into superframes containing time slots numbered relative to the start of the superframe. Additionally, the network manager **27** may maintain a global absolute slot count which may reflect the total of number of time slots scheduled since the start-up of the wireless HART network **14**. This absolute slot count may be used for synchronization purposes.

The wireless HART protocol **70** may further define links or link objects in order to logically unite scheduling and routing. In particular, a link may be associated with a specific network device, a specific superframe, a relative slot number, one or more link options (transmit, receive, shared), and a link type (normal, advertising, discovery). As illustrated in FIG. **2**, the data link **76** may be frequency-agile. More specifically, a channel offset may be used to calculate the specific radio frequency used to perform communications. The network manager **27** may define a set of links in view of the communication requirements at each network device. Each network device may then be configured with the defined set of links. The defined set of links may determine when the network device needs to wake up, and whether the network device should transmit, receive, or both transmit/receive upon waking up.

Other layers of the wireless HART protocol **70** are also illustrated in FIG. **2**. Both the existing HART protocol **72** and the wireless HART protocol **70** are loosely organized around the well-known ISO/OSI 7-layer model for communications protocols. In the wireless expansion of HART technology, three physical layers and two data-link layers may be supported: the wired and the wireless mesh. Because the wireless HART protocol described herein allows deployment of mesh topologies, a significant network layer **78** may be specified as well.

As indicated above, a superframe may be understood as a collection of time slots repeating in time. The number of slots in a given superframe (superframe size) determines how often each slot repeats, thus setting a communication schedule for network devices that use the slots. Each superframe may be associated with a certain graph identifier. In some embodiments, the wireless HART network **14** may contain several concurrent superframes of different sizes. Moreover, a superframe may include multiple radio channels, or radio frequencies.

Further, the transport layer **80** of the wireless HART protocol **70** allows efficient, best-effort communication and reliable, end-end acknowledged communications. As one skilled in the art will recognize, best-effort communications allow devices to send data packets without an end-to-end acknowledgement and no guarantee of data ordering at the destination device. User Datagram Protocol (UDP) is one well-known example of this communication strategy. In the process control industry, this method may be useful for publishing process data. In particular, because devices propagate process data periodically, end-to-end acknowledgements and retries have limited utility, especially considering that new data is generated on a regular basis.

In contrast, reliable communications allow devices to send acknowledgement packets. In addition to guaranteeing data delivery, the transport layer **80** may order packets sent between network devices. This approach may be preferable for a request/response traffic or when transmitting event notifications. When the reliable mode of the transport layer **80** is used, the communication may become synchronous.

Reliable transactions may be modeled as a master issuing a request packet and one or more slaves replying with a response packet. For example, the master may generate a certain request and can broadcast the request to the entire network. In some embodiments, the network manager **27** may use reliable broadcast to tell each network device in the wireless HART network **14** to activate a new superframe. Alternatively, a field device such as the sensor **30** may generate a packet and propagate the request to another field device such as the portable HART communicator **55**. As another example, an alarm or event generated by the **34** field device may be transmitted as a request directed to the gateway **22**. In response to successfully receiving this request, the gateway **22** may generate a response packet and send it to the device **34** acknowledging receipt of the alarm notification.

Referring again to FIG. **2**, the session layer **82** may provide session-based communications between network devices. End-to-end communications may be managed on the network layer by sessions. A network device may have more than one session defined for a given peer network device. It is contemplated that in some embodiments, almost all network devices may have at least two sessions established with the network manager **27**: one for pairwise communication and one for network broadcast communication from the network manager **27**. Further, all network devices may have a gateway session key. The sessions may be distinguished by the network device addresses assigned to them. Each network device may keep track of security information (encryption keys, nonce counters) and transport information (reliable transport sequence numbers, retry counters, etc.) for each session in which the device participates.

Finally, both the wireless HART protocol **70** and the wired HART protocol **72** may support a common HART application layer **84**. The application layer of the wireless HART protocol **70** may additionally include a sub-layer **86** supporting auto-segmented transfer of large data sets. By sharing the application layer **84**, the protocols **70** and **72** allow for a common encapsulation of HART commands and data and eliminate the need for protocol translation in the uppermost layer of the protocol stack.

In the example illustrated in FIG. **3**, it is important to consider the location of the wireless devices on each tank so that the wireless network **14** can establish itself in an efficient and reliable form. In some cases, it may be necessary to add routers **60** in those locations where plant equipment could block or seriously affect a wireless connection. Thus, in this and in similar situations, it is desirable that the wireless network **14** be self-healing. To meet this design requirement, the wireless network **14** may define redundant paths and schedules so that, in response to detecting a failure of one or more direct wireless connections **65**, the network **14** may route data via an alternate route. Moreover, the paths may be added and deleted without shutting down or restarting the network. Because some of the obstructions or interference sources in many industrial environments may be temporary or mobile, the wireless HART network **14** may be capable of automatically reorganizing itself. Specifically, in response to one or more predetermined conditions, pairs of field devices may recognize each other as neighbors and thus create a direct wireless connection **65** or, conversely, dissolve previously direct wireless connections **65**. The network manager **27** may additionally create, delete, or temporarily suspend paths between non-neighboring devices.

Irrespective of whether a particular network configuration is permanent or temporary, the wireless HART network **14** requires a fast and reliable method of routing data between nodes. In one possible embodiment, the network manager **27** analyzes the information regarding the layout of the network, the capability and update rate of each network device, and other relevant information. The network manager **27** may then define routes and schedules in view of these factors.

FIGS. **4**-**6** illustrate some of the network topologies compatible with the routing and device addressing techniques of the present disclosure. In particular, FIG. **4** illustrates a network **150** arranged in a star network topology. The star network **150** includes a routing device **152** and one or more end devices **154**. The routing device **152** may be a network device arranged to route data while the end device **154** may be a network device arranged to send data only on its own behalf and to only receive data addressed to the end device **154**. Of course, the routing device **152** may also be a recipient and originator of data and may perform routing functions in addition to other tasks. As illustrated in FIG. **4**, end devices **154** may have a direct connection **165** to the routing device **152** but end devices **154** cannot be connected directly in a star topology. The direct connection **165** may be a direct wireless connection **65** or a wired connection.

The end device **154** may be different or may be the same type of physical device as the routing device **152** and may be physically capable of routing data. The routing capability of the end device **154** may be disabled during the installation of the end device **154** or, alternatively, during operation of a corresponding network (such as the wireless HART network **14**). Moreover, the routing capability of the end device **154** may be disabled by the end device **154** itself or by a dedicated service such as the network manager **27**. In other embodiments, the end device **154** may contain only limited firmware or software and, as a result, may not be capable of routing data at all. In some sense, the star network **150** corresponds to the simplest of possible topologies, and may be appropriate for small applications that require low power consumption and low latency. Additionally, one of ordinary skill in the art will notice that the star network **150** is deterministic because there is only one possible route between the routing device **152** and a particular end device **154**.

Moving on to FIG. **5**, a network **170** is arranged in a mesh network topology. Each network device of the mesh network **170** is a routing device **152**. Mesh networks provide a robust network with multiple paths. In wireless applications, mesh networks are better able to adapt to changing RF environments. For example, the device **174** of the network **170** may send data to the device **176** via an intermediate hop **178** or an intermediate hop **180**. As illustrated in FIG. **5**, both a path **182** and a path **184** enable the routing device **174** to send data to the routing device **176**, providing redundancy and thus improved reliability to the network **170**.

Referring again to FIG. **5**, each of the paths **182** and **184** is a unidirectional path. In other words, the routing devices **174**, **178**, and **176**, along with the path **182** form a directed graph. In one embodiment of the wireless HART network **14**, all direct wireless connections **65** are unidirectional. Other embodiments which include bidirectional wireless connections are also contemplated. However, it should be noted that defining direct connections unidirectionally may provide an important advantage in designing wireless networks. More specifically, defining unidirectional connections automatically implies the definition of senders and receivers in the network. Meanwhile, a bidirectional connection additionally requires a sharing or conflict resolution scheme for the two hosts which may both receive and transmit at the same time.

Another network topology is illustrated in FIG. **6**. The network **190** incorporates elements of both star and mesh topologies. In particular, the star mesh network **190** includes several routing devices **152** and end devices **154**. The routing devices **152** may be connected in a mesh format and may support redundant paths. The selection of a particular topology may be performed automatically by a network component, such as the network manager **27**, or by a user configuring the network. In particular, the user may choose to override the topology selected by the network manager **27** or the default topology associated with the wireless HART protocol **70**. It is contemplated that in most applications, mesh topology may be the default topology because of the inherent reliability, efficiency, and redundancy of this topology. Clearly, because wireless HART devices may act as router devices, several different configurations may be compatible with the same physical disposition of field devices and routers.

The wireless HART protocol **70** may be configured in a number of different topologies to support various application requirements. As a result, wireless HART may support several methods of routing. In general, routing requires that each device be assigned a specific address on the network. Once every potential receiver of data acquires some form of unambiguous identification with respect to other network elements, decisions related to routing may be made by individual devices such as field devices **30**-**40**, by a centralized dedicated service such as the network manager **27**, or by individual devices acting in cooperation with the centralized service. Routing decisions can be made at the originating point, or source of a data packet or at a centralized location. Moreover, routing decisions can be adjusted at each intermediate stop, or "hop," in the path of the packet from the source to a destination.

In one contemplated embodiment, the wireless HART protocol **70** provides at least two approaches to routing that may be selected according to the specific requirements and conditions of a given system, such as the physical layout of the network elements that make up the system, the number of elements, the expected amount of data to be transmitted to and from each element, etc. Moreover, the two approaches may be used by a particular network at the same time and each may be selectively applied to a particular type of data or to a particular host or a set of hosts. As explained in greater detail below, the wireless HART protocol **70** may route certain type of data by defining a set of directed graphs, selecting the information relevant to each network device, and communicating the relevant information to each network device. For other types of data, the wireless HART protocol **70** may define routes between pairs of networks devices and route a data packet by specifying the complete list of intermediate hops in the packet header.

In mathematical theories and applications, a graph is a set of vertices (nodes such as **152** or **154**) and edges (direct connections **65** or **165**). The wireless HART protocol **70** may use graphs to configure paths connecting communication endpoints such as the device **30** to the gateway **22**, for example. In some embodiments, graphs and the associated paths are configured by the network manager **27**. The network manager **27** may also configure individual network devices such as field devices **30-40**, routers **60**, etc. with partial graph and path information. The wireless HART network **14** may contain multiple graphs, some of which may overlap. Further, a certain network device may have paths of multiple graphs going through a device, and some of the paths may direct data to the same neighbor of a device. In one embodiment, graphs are unidirectional and every graph in a network is associated with a unique graph identifier.

In the example illustrated in FIG. **7**, the network **200** may define several directed graphs, each graph including either the gateway device **22** or a second gateway device **202** as the terminal node. In other words, the paths of each graph in the exemplary network **200** lead to and terminate at one of the two gateways **22** and **202**. Specifically, a graph **210** (indicated by a solid black line) may include network devices **212**, **214**, **216**, **218**, and the gateway **22** while the paths associated with the graph **210** may include direct wireless connections **222**, **224**, **226**, and **228**. A graph **240** (indicated by a dotted black line) may include network devices **212**, **216**, **218**, **242**, and the gateway **202**, with a path that includes direct wireless connections **244**, **246**, **248**, **250**, and **252**. In the directed graph **210**, the network device **212** may be called the head of the directed graph **210** and the gateway **22** may be called the tail of the directed graph **210**. Similarly, the network device **212** is the head of the directed graph **240** and the gateway **202** is the tail of the directed graph **240**. The network manager **27** or, under certain operating conditions, a backup network manager **257** may define graphs **210** and **240** and communicate partial definitions of the graphs to the network devices **212-218** and **242**. In some embodiments, the gateway devices **22** and **202** may not require the information regarding the graphs **210** and **240** in those cases where the path terminates at one the gateway devices **22** or **202**. However, it will be appreciated that the gateway devices **22** and **202** may also originate data and may store information regarding one or more graphs with paths originating from the gateway device **22** or **202**. A path of a certain graph may traverse the gateway device **22** or **202**; however, the exemplary network **200** defines paths either originating or terminating at the gateway device **22** or **202**.

The exemplary network **200** may provide bidirectional communications between one of the network devices **212-218** or **242** and the gateway devices **22** and **202** by defining two unidirectional graphs for each pair of communicating devices. Thus, in addition to the graph **210**, the network **200** may define an "inverse" graph (not shown) originating at the gateway **22** and terminating at the communicating device **212**. This graph and graph **210** may include different intermediate nodes and direct wireless connections. Moreover, although these two graphs connect the same pair of devices, the graph **210** and the inverse of the graph **210** may have a different number of hops. Of course, in some possible configurations of the network **210**, these graphs may include the same nodes and direct wireless connections and thus each pair of adjacent hops included in both graphs may have two unidirectional links, with one link defining upstream communication and the other link defining downstream communication. However, it will be appreciated that these two graphs may not necessarily provide the same delay or even signal quality.

To send a data packet along a certain graph, the source network device may include an identifier of the graph in the header or trailer of the data packet. The data packet may travel via the paths corresponding to the graph identifier until it either reaches its destination or is discarded. In order to be able to route packets in the graph **210**, for example, each network device that belongs to the graph **210** needs to be configured with a connection table which contains entries that include the graph identifier and address of a neighbor network device which belongs to the same graph and is one hop closer to the destination. For example, the network device **216** may store the following connection table:

Graph identifier	Node
210	218
240	218
240	242

while the network device **242** may store the following information in the connection table:

Graph identifier	Node
240	202

While the exemplary connection tables above simply list the devices associated with a particular entry, it will be noted that the Node column of the connection table may store the address of the neighboring device as defined in the addressing scheme of the network **200** or wireless HART network **14**.

In another embodiment, the Node column may store the nickname of the neighboring device, an index into an array storing full or short addresses of the neighbors, or any other means of unambiguously identifying a network device. Alternatively, the connection table may store graph identifier/wireless connection tuples as illustrated below:

Graph identifier	Connection
210	226
240	246
240	248

In other words, the connection table may list one or more direct wireless connections **65** corresponding to a particular graph. The network device **216** may, for example, consult the connection table and transmit a packet carrying the graph identifier **240** via the direct wireless connection **246** or **248**.

As illustrated in FIG. **7** and in the tables above, redundant paths may be established by having more than one neighbor associated with the same graph identifier. Thus, a packet arriving at the network device **216** and containing the graph identifier **240** in the header or trailer may be routed to either or both the network device **218** or the network device **242**. While executing the routing operation, the network device **216** may perform a lookup in the connection table by the graph identifier **240**, and send the packet to either or both of the network devices **218** and **242**. Moreover, the routing selection between two or more possible hops may be random or may be carried out according to a predefined algorithm. For example, the selection may be made in consideration of a load balancing objective or in view of the delivery statistics. Thus, the network device **216** may learn, through a peer network device or from the network manager **27**, that selecting the network device **218** as the next hop while routing packets along the graph **240** has a lower probability of delivering the packet successfully or a longer delay in delivery. The network device **216** may then attempt to route more of possibly all of the packets associated with the graph **240** to the network device **242**.

In one embodiment, receipt of packets by a neighboring device is acknowledged by a confirmation packet. In the example above, once the neighboring network device **218** or **242** acknowledges receipt of the packet, the network device **216** may release it. If, on the other hand, the acknowledgement is not received within a predefined time period, the network device **216** may attempt to route the packet via the alternate hop. Additionally, the network device **216** may collect statistics of both successful delivery attempts and of failed delivery attempts. The subsequent routing decisions, such as selecting between the hops **218** and **242**, may include the adjusted statistical data. Of course, the network device **216** may apply the statistics related to network devices **218** and **242** to other relevant graphs and may also communicate the statistics to other network devices, either directly or via the network manager **27**.

As discussed above, in the graph routing approach, a network device sends packets with a graph identifier in a network header along a set of paths to the destination. Importantly, a graph identifier alone is sufficient for routing packets and, while other routing information may be included in the header, each packet can be properly delivered based solely on the graph identifier. All network devices on the way to the destination may be pre-configured with graph information that specifies the neighbors to which the packets may be forwarded. Because graph routing requires pre-configuration of intermediate network devices for each potential destination, graph routing may be better suited for communications from a network device to a gateway and from a gateway to a network device.

The wireless HART network **14** or the network **200** may also use source routing. In source routing, pre-configuration of the forwarding devices is not necessary. To send a packet to its destination using source routing, the source network device may include in the header of a packet an ordered list of devices through which the packet must travel. As the packet is routed, each routing device may extract the next node address from the packet to determine the next hop to use. Consequently, using source routing requires knowledge of network topology. If, however, a certain network device does not find itself on the routing list, the network device may send the packet back to the first device specified in the source routing list. Source routing allows packets to go to an arbitrary destination without an explicit set up of intermediate devices.

For example, the network device **212** may send a packet to the the gateway **22** by specifying the complete path in the packet header or trailer. Referring again to FIG. **7**, the network device **212** may generate a list containing the addresses of network devices **214** and **218** and send the list along with the packet to the first hop on the list, the network device **214**. The network device **214** may then traverse the list, locate the identity of the network device **214** and extract this field from the list, identify the network device **218** as the next hop for the received packet, and finally send it to the network device **218**. The source routing list may reside in the optional area of the network header, and may be of variable size depending on number of hops to the destination.

In one embodiment, only those network devices that have obtained full network information from the network manager **27** use source routing because only the network manager **27** knows the topology of the network. An additional limitation of source routing is that it provides no redundancy at intermediate network devices because each packet contains an explicit list of hops to take and no alternatives. Thus, if one of the devices fails to send the packet as specified, no alternate direction is taken. It is therefore the responsibility of the network manager **27** to detect the failure and reprogram the source with an alternate route. To facilitate the detection of such error cases, the wireless HART protocol **70** may require network devices to send a routing failure notification back to the network manager **27**. In another embodiment, the routing list may specify alternate routes in addition to the route selected by the sender. In yet another embodiment, primary and one or more alternate routes may be merged to avoid duplication of common parts of the path in the packet header or trailer.

In accordance with some of the embodiments discussed above, the network manager **27** contains a list of all devices in the network. The network manager **27** may also contain the overall network topology including a complete graph of the network and portions of the graph that have been communicated to each device. The network manager **27** may generate the route and connection information using the information that the network manager **27** receives from the network devices **30**-**40**, **50**, **60**, **55**, **212**-**218**, etc. The graph of the network is built from the list of network devices and their reported neighbors. The network manager **27** may also be responsible for generating and maintaining all of the route information for the network. In one embodiment, there is always one complete network route and several special purpose routes which are used to send setpoint and other settings from the gateways **22** or **202** to the final control commands. Further, there may be broadcast routes used to send broadcast messages from the network manager **27** or **257** to all of the devices of the network **14** or **200**. Still further, the network manager **27** may also carry out the scheduling of network resources once the routing information and burst mode update rates are known.

When devices are initially added to the network **200** or **14**, the network manager **27** may store all neighbor entries as reported from each network device. The network manager **27** may use this information to build an initial complete network graph (or set of network graphs including forward graphs and reverse graphs) and revise the graph in operation. Each network graph may be developed by optimizing several properties including hop count, reporting rates, power usage, and overall traffic flow as reflected by the statistics gathering discussed above. One key aspect of the topology is the list of connections that connect devices together. Because the presence and health of individual connections may change over time, the network manager **27** may be additionally programmed or configured to update the overall topology, which may include adding and deleting information in each network device. In some embodiments, only the network manager **27** or **257** and the gateway **22** or **202** know enough information to use source routing. More specifically, it may be desirable not to allow peer-to-peer communication between any two arbitrary devices for security purposes.

In short, graph routing may direct traffic both upstream and downstream with respect to the network manager **27** or gateway **22** and both graph and source routes can be optimized to satisfy applications with low latency requirements, which includes measurement information that is transferred from network devices to the gateway and control information that is transferred from gateway devices to final control commands such as regulating valves, on-off valves, pumps, fans, dampers, as well as motors used in many other ways.

In some embodiments, path redundancy is a matter of policy of the network manager **27** rather than a coincidental overlap of graphs. In other words, the network manager **27** may attempt to define at least two neighbors for each device. Thus, the network manager **27** may be configured to actively pursue a mesh or a star mesh topology. The wireless HART protocol **70** may thus provide a very high end-to-end data reliability. From the physical perspective, each field device should be within communication range of at least two other devices that can receive messages from the field device and forward them.

The network manager **27** may additionally verify each graph definition in order to ensure that no loops have been formed. In those embodiments where the network manager **27** actively pursues path redundancy and defines many graphs of various sizes, a communication path may be sometimes erroneously defined to direct data packets from a source back to the same source. In accordance with such faulty graph definition, a packet may be routed back to the source directly from the source or may visit one or more intermediate hops prior to arriving back at the source. Loop verification may be performed each time the topology of the associated network changes, such as due to an addition or removal of a device, or whenever the network manager **27** adjusts the routing graphs and schedules for any reason. Alternatively, the network manager **27** may perform loop checking periodically as a background task.

As indicated above, devices involved in routing store or obtain a different graph route, the source route, or to the address of the destination in order to deliver and properly relay data packets. The address of each network device must be globally unique in order for the wireless HART network **14** to properly co-operate with a larger network which may include wired HART devices. For this reason, the wireless HART protocol **70** provides an unambiguous addressing scheme and additionally provides an efficient mapping of addresses to a larger network context. Importantly, the wireless HART protocol **70** provides an addressing scheme compatible with the addressing scheme used with wired HART devices.

FIG. **8** illustrates an exemplary architecture of the network design tool **45**. An engine **300** may contain the tool logic and may include a graph generator **302** and a schedule generator (or "scheduler") **304** which may, in turn, interact with each other to generate or make combined routing and scheduling decisions. The engine **300** may also include a set of optimization rules **306**. Each of the optimization rules **306** may contain an algorithmic description of a certain aspect of the optimization strategy and may also depend on one or more user parameters. For example, one of the optimization rules **306** may state that creating more than X number of connections to a certain node is prohibited. The user may assign a specific value to X via the user interface **312** so that the engine **300** can apply the rule during operation. In short, the engine **300** may encapsulate the intelligent components of the network design tool **45**. The engine **300** may interact with one or more instances of a user interface **310-312**. In some embodiments, the network design tool **45** may run in a distributed manner and may provide simultaneous access to the functionality of the engine **300** to multiple operators. For example, the workstation **16** may execute or provide the user interface **310** while the remote host **41** may execute the engine **302** and the user interface **312**. Each of the user interface instances **310** and **312** may be tailored according to the hardware availability at each corresponding host and may further be tailored to the specific requirements and preferences of the operator such as language, for example. As illustrated in FIG. **8**, the user interface **312** may interact with such physical devices as a mouse **314**, a keyboard **316**, a monitor **318**, and possibly a printer (not shown). One skilled in the art will further appreciate that the user interface **312** or the user interface **310** could be similarly connected to other input and output devices.

As indicated above, the network design tool **45** may provide a user interface via one or several interactive windows. As one familiar with the Microsoft Windows™ or similar graphic environment will recognize, an interactive window typically includes a canvass area containing text and graphics, a toolbar providing access to various functions of the corresponding software, buttons disposed on the toolbar providing shortcuts to the frequently used functions or graphical objects, and vertical and horizontal scrollbars which allow user to align the visible window with specific parts of the canvas. Generally speaking, the network design tool **45** may be implemented on any operating system. However, the operating system on which the user interface component of the network design tool **45** is executed preferably supports a graphical interface. In the embodiments discussed below, the network design tool **45** allows users to manipulate visual objects in form of geometric shapes such as circles, squares, and arrows, although other graphic objects may be used. Further, the network design tool **45** may render the graphic objects on the monitor **318** in different colors to indicate the state of the object or convey other additional information.

Referring again to FIG. **8**, the engine **300** may also interact with one or more instances of a live network interface **320**. The live network interface **320** may report data from the wireless HART network **14** to the engine **300**. In particular, the live network interface **320** may report the measurements related to the signal strength, time delay, and other network performance data measured by the network devices of the network **14**. In response to receiving network performance data from the network **14** via the live network interface **320**, the engine **300** may communicate these reports to one or more users via the user interfaces **310** or **312**. Additionally, the engine **300** may automatically adjust routing and scheduling of a network model **324** corresponding to the wireless network **14**. As illustrated in FIG. **8**, the network model **324** may be stored in a memory **326** coupled to one of the hosts **16**, **18**, **41**, **47**, or **55**.

Referring to FIG. **9**, the network design tool **45** may present, to one or more users interacting with the user interface modules **310** or **312**, a main menu **340** which may provide access to such features of the network design tool **45** as network configuration and network simulation. In the exemplary embodiment illustrated in FIG. **9**, the main menu **340** may include a file submenu **342**, a graph generating options submenu **344**, a topology submenu **346**, and a schedule submenu **348**. Specifically, the file submenu **342** may provide a standard set of file manipulation functions such as saving the network model **324** in the memory **326** or other storage location or sending a file containing the network model **324** to a printer. Meanwhile, the graph generating options submenu **344** may provide access to path selection rules **350**, graph type selection **352**, and other user-configurable rules and parameters.

By invoking the topology submenu **346** from the main menu **340**, the user may access an interactive canvass screen containing a drawing corresponding to the network model **324**. The topology submenu **346** may include the interfaces **354** for adding and deleting nodes, editing signal strength, changing the views of the network model **324**, and automatic graph generation. On the other hand, the schedule submenu **348** may present several options with respect to displaying the generated schedules. For example, the graph view **356** may render a multi-color, user-friendly visual representation of an entire network schedule, also referred to as the master schedule. The text view **358** may offer a textual description of the same master schedule. Finally, the XML view **360** may generate a textual description of the master schedule which conforms to the rules of XML.

Moving on to FIG. **10**, an interactive window **380** may present a view of the network model **324** accessible to a user via the topology submenu **346**. The interactive window **380** may include a canvass area **382**, a toolbar **384**, and scrollbars **386-388**. The toolbar **384** may provide interactive access to the submenus **342-348** in form of pull-down lists, for example. Additionally, the toolbar **384** may include one or more shortcut buttons **390**. The shortcut buttons **390** may provide user with an easy and efficient method of adding symbols representing various network devices to the canvass area **382**. In particular, the user may operate one of the shortcut buttons **390** to select a symbol representing a gateway device, a network access point, a field device, a router, etc. Additionally, the toolbar **384** may include non-network element buttons **392** corresponding to physical obstructions such as walls. The user may then drag the selected symbol onto the canvass area **382** using the mouse **314** or a similar pointing device. In other embodiments, the user may operate keyboard keys to enter text commands in order to select symbols and position these symbols in the canvass area **382**.

The canvass area **382** may be a symbolic representation of a plant area in which the wireless HART network **14** operates. The placement of symbols representing network devices may accurately reflect the relative distances between the devices. In other words, the graphical representation of the model **324** on the canvass area **382** may be to-scale. It is also contemplated that the canvass area **283** may include a grid (not shown) in order to simplify the task of accurately placing the symbols relative to each other. In yet another embodiment, the canvass area **283** may include a schematic representation of the plant. For example, the canvass area **382** may include two-or three-dimensional, to-scale representation of tanks, valves, pipes, and other components of a process control system so that the user may easily see the correspondence between the model **324** and the actual geographic positioning of the corresponding physical devices. Still further, the canvass area **382** may schematically represent the actual physical obstructions such as walls as well as inaccessible or "forbidden" areas such as hallways or offices. In accordance with this embodiment, the network design tool **45** may take physical obstructions into account without requiring the user to specify the draw an obstruction symbol by operating the obstacle element buttons **392**.

After placing a symbol representing a network device or an obstacle on the canvass area **382**, the user may further configure the modeled device by selecting the symbol, invoking an interactive parameterization window, and entering a set of parameters specific to the modeled device. In the example illustrated in FIG. **10**, the user has placed several network devices symbols on the canvass area **382**, including the device symbol **400**. More specifically, the user may have selected the symbol representing a field device from among the shortcut buttons **390**, activated the symbol by a mouse click or similar method, and dragged a copy of the symbol to the desired location in the canvass area **382**. In this exemplary embodiment, the field device symbol is a circle enclosing a letter "D," the letter serving as a visual aid in differentiating between various network device types. The user may have then invoked a parameterization menu by clicking on a predefined mouse button, for example, and specified that the physical field device corresponding to the device symbol **400** is powered by means of a battery. As a result, the wireless network device tool **45** may display a battery symbol **402** next to the device symbol **400**.

The user may further specify, for each field device, the rate at which the device reports measurements or other data to another network device. This report rate is also known as burst rate. In the example of the wireless HART network **14**, field devices report data upstream to the gateway device **22**. The wireless network device tool **45** may display the burst rate as an indicator **404** placed next to the device symbol **400**. The user may further specify the power at which the physical device corresponding to the device symbol **400** transmits radio signals. In one embodiment, the user may invoke a power setting option by pressing on a predefined keyboard or mouse key. In response to detecting the key press event, the network design tool **45** may display an interactive window in which the user may enter the signal strength measured in watts, for example. Alternatively, the user may configure the network design tool **45** to associate each network device with a same predetermined power level in order to simplify the process of configuring the network model **324**.

As device symbols are added to the canvass area **382**, the network design tool **45** may assign a sequence number to each new symbol. In another embodiment, the network design tool **45** may assign numbers according to the order in which the symbols are encountered in breadth-first traversing of a corresponding graph, with one of the gateway symbols assigned the sequence number **0** and placed at the head of the graph. In the example illustrated in FIG. **10**, the network design tool **45** may display the sequence number as an indicator **406** next to the device symbol **400**.

Referring again to FIG. **10**, the user may have placed a gateway symbol **410** and a network access point symbol **412** on the canvass area **382**. As discussed above with reference to FIG. **1**, a gateway device **22** may be connected to multiple network access points **25** in a highly reliable and efficient manner, such as over a pair of dedicated wires. The network design tool **45** may indicate the relative reliability of the gateway-to-network access point connection by means of a solid line representing a wire link **414**. In contrast, the network design tool **45** may illustrate wireless links by means of a dotted line as, for example, in the case of a wireless link **416** between the device symbols **400** and **412**. Of course, the wireless and wired connections between network devices may also be depicted in any other manner and the lines **414** and **416** are provided by way of example only.

Next, the network design tool **45** may begin analyzing the network model **324** by evaluating the quality of every wireless link between every pair of network devices in view of such factors as the signal strength at each device, the distance between the devices, the power of each device, the type of receiving device, and the presence of obstacles which may attenuate the radio signal. Because each device may transmit radio signals at a unique power level, the parameters of a uni-directional link from device A to device B may be different from the parameters of a uni-directional link from device B to device A. For example, the network design tool **45** may estimate the quality of a uni-direction wireless link **404** by calculating the attenuation of a radio signal transmitted by the physical device corresponding to the device symbol **400** over the distance between the physical network devices represented by symbols **400** and **412**. As indicated above, the distance between the devices represented by symbols **400** and **412** may be accurately reflected by the relative placement of the symbols **400** or **412** if the model **324** is drawn to scale. Alternatively, the user may specify the distance between a pair of network devices by selecting a wireless link on the network model **324**, activating an appropriate setting screen, and entering the distance in feet or meters, for example. Upon completing the calculation, the network tool **45** may display a signal quality indicator **420** next to the wireless link **416**. Referring again to FIG. **10**, a symbol **422** representing a field device and a symbol **424** representing a router device may be connected by a wireless link may be separated by a distance X while the symbol **422** and a symbol **426** may be separated by a distance Y. The network design tool may accordingly display indicators **428** and **430** next to unidirectional links extending from device **422** to devices **424** and **426**, accordingly.

The network design tool **45** may assess each wireless link as the user adds new network devices to the canvass **382**. Thus, if the network model **324** includes network device symbols S**1**, S**2**, . . . Sn, the addition of a device symbol Sn+1 requires that the network design tool **45** evaluate n new links between each pair of symbols {S**1**, Sn+1}, {S**2**, Sn+1}, . . . {Sn, Sn+1}. In order to avoid clutter, the toolbar **384** may include buttons **432** which toggle optimized presentation modes. More specifically, one of the toggle buttons **432** may cause the network design tool **45** to display only those wireless links that pass a predefined quality criteria, such as, for example, the signal quality exceeding −10 dB. Conversely, another toggle button **432** may cause the network design tool **45** to display all wireless links, irrespective of the quality.

A collection of wireless links which pass a predefined set of quality criteria, along with the wired links connecting gateway devices to network access points, forms a master graph **435**. Additionally, each path between a pair of network devices, such as the path from the field device symbol **422** to the gateway device symbol **412**, forms an individual graph. Moreover, each graph may be an upstream or downstream graph with respect to one of the gateways. The network design tool **45** may illustrate the direction of each wireless link by means of an arrow, such as the arrow on the link **416** pointing in the direction of the network access symbol **412** to indicate that the link **416** is part of an upstream graph. The toolbar **384** may also contain a graph mode selector **437** which the user may operate in order to select between such viewing options as the display of downstream graphs only, the display upstream graphs only, or the simultaneous display of both upstream and downstream graphs.

As illustrated in FIG. **11**, an interactive screen **450** may correspond to the graph generating options submenu **344**. The user may use the interactive screen **450** in order to configure the preferences regarding path selection and scheduling on a network simulated by the network model **324**. In this exemplary embodiment, the interactive screen **450** may include a network type selector **452** which allows the selection between star, mesh, and star mesh topologies. If, for example, the user selects star topology via the network type selector **452**, the network design **45** automatically defines wireless connections consistent with star topology, with a gateway device or a network access point as a center. In the case of the network model illustrated in FIG. **10**, each wireless connection between a pair of field devices is eliminated. Instead, the network design tool **45** may simulate a wireless connection between such device symbols as **412** and **422**, **412** and **424**, etc.

Further, the interactive screen **450** may include a threshold signal strength selector **455**. By using the selector **455**, the user may specify the minimum strength of a signal transmitted from a sender device which must be detected by a recipient device in order to consider a link between the sender device and the recipient device acceptable for use in a graph. Of course, the user may use the selector **455** at any time during the configuration of the network model **324** to change this minimum signal strength value. In response to the user entering a new value by means of the selector **455**, the network design tool **45** may re-evaluate each pair of devices and, in some cases, either delete or add wireless links. In the example illustrated in FIG. **11**, the selector **455** includes a scrollbar and a text indicator. However, one of ordinary skill in the art will recognize that any graphical or textual implementation of the selector **455**, as well as of other selectors discussed herein, is equally possible.

A hysteresis level selector **457** may allow the user to specify a signal strength at which the network design tool **45** begins re-evaluating the network graph. If the feedback information reported to the network design tool **45** from the live wireless HART network **14** indicates a change in the signal level of one or more links, the network design tool **14** may refer to the value set via the hysteresis level selector **457** to decide when graph re-evaluation must begin. For example, the strength of a signal at a particular link may drop slightly below the minimum level configured via the selector **455** but may still be above the hysteresis level configured via the selector **457**. In this case, the network design tool **45** may not yet proceed with graph evaluation in order to avoid such situations as, for example, re-evaluating a network graph when the signal strength periodically drops slightly below and later rises above the threshold signal level.

The interactive screen **450** may also include a neighbor number selector **459**. By using the selector **459**, the user may specify the maximum number of neighboring devices to consider at each individual network device during graph construction. For example, the network device represented by the symbol **400** may potentially establish wireless links with all seven wireless network devices corresponding to the network model **324**. Of course, each wireless link may have different signal strength due to the distance from the transmitting device and other physical factors and, therefore, a different overall link quality. Thus, it may not be prudent to attempt establishing a connection with each potential neighbor. Instead, an efficient graph selection strategy may focus on only a limited number of potential neighbors. The value selected via the selector **459** may restrict the number of potential neighbors to a small value such as 3, for example, even if more than 3 neighbors of a certain device satisfy the signal strength requirement configured through the selector **455**.

Further, the interactive screen **450** may include a selector **461** for specifying the criteria for choosing between a multi-hop link characterized by relatively good signal strength and a single-hop link characterized by relatively poor signal strength. In general, a single-hop link between a pair of devices is preferable because of the lower latency and relative simplicity of the scheduling, among other factors. However, the signal quality of a single-hop may be poor compared to a multi-hop link connecting the same pair of devices. In order to make a proper selection between these options, the tradeoffs associated with each approach must be quantified and compared. In the exemplary embodiment illustrated in FIG. **11**, the user may specify a number of decibels by which the signal strength of a multi-hop must exceed the signal strength of a corresponding single-hop link in order for the network design **45** to choose the multi-hop link over the single-hop link.

Referring again to FIG. **11**, the interactive screen **450** may further include a minimum hop number selector **463**. The user may specify the minimum number of hops for the network design tool **45** to consider when constructing graphs. The minimum number of hops may default to, for example, "1" but could default to another number if so desired. A maximum hop number selector **465** may allow the user to specify the maximum length of an individual graph measured in hops and may default to a particular number, such as "4") although the default may be different for different uses. For example, the user may decide that the process control system using the wireless HART network **14** may not tolerate delays associated with default setting of 4-hop paths between devices and may set the hop limit at 3 via the selector **465**. As a result, the network design tool **45** will not define graphs and, therefore, paths which include more than 3 hops even if this limitation results in the selection of wireless links of a relatively poor quality. The selectors **450** and **465** allow the tool or engine **300** to consider both the minimum number of hops (e.g., default to 1) and the maximum number of hops (e.g., default to 4) when developing a set of graphs and routing schedules for the network. In addition, if desired, these and each of the other selectors described herein may be settable on a per-node basis, which gives the user the ability to decrease latency to critical items such as valves.

In the exemplary embodiment of the interactive screen **450**, the user may additionally quantify the desirability of routing data through network devices powered by a permanent power source such as a 110V AC line as compared to battery-powered network devices. For example, the user may enter the number "3" into a window of a disadvantage factor selector **467**. As a result, the network design tool **45** may consider each hop through a powered network node 3 times as preferable as a hop through an unpowered network node if all other factors are the same.

In general, the network design tool **45** and in particular the engine **300**, when making graph and scheduling decisions, may weigh in multiple factors by assigning numerical desirability indicators to potential links or graphs and by applying the optimization rules **306** in a predefined order. Because some of the rules may direct the network design tool **45** toward incompatible approaches, such as bypassing a certain node according to one rule and routing data through the same node according to another rule, assigning relative priority to the optimization rules **306** helps the network design tool **45** resolve these conflicts. FIG. **11**A illustrates an exemplary procedure **500** which the network design tool **45** may execute as part of automatic graph definition. As discussed above, the network design tool **45** may invoke the procedure **500** when the user adds new devices to the canvass **382**, when the feedback information regarding the actual performance of the wireless HART network **14** arrives at the live network interface **320**, or in response to a user operation such as a predefined key press or menu option selection. It will be appreciated that while FIG. **11**A illustrates the application of the optimization rule **306** in form of a sequence of steps, some of the steps may also be executed in parallel. Moreover, some of the optimization rules **306** may not present a conflict with the other rules at any time and may therefore apply at any stage of the procedure **500**.

A principle **502** may be applied as a first step of executing the procedure **500**. In particular, the procedure **500** may first attempt to define, whenever possible, single-hop paths to the gateway **22** or, in case redundant gateway devices are available, to the virtual gateway **24**. In those embodiments where the gateway **22** communicates with the wireless HART network **14** via one or more network access points **25**, the single-hop paths may be defined relative to one of the network access points. Of course, the procedure **500** may not violate the limits configured via the interactive **450** and, in particular, the threshold signal strength limitation specified via the selector **455**. Referring back to the network model **324** illustrated in FIG. **10**, the procedure **500** has determined, for example, that the physical device corresponding to the device symbol **400** may establish a single-hop wireless link **416** to the network access point corresponding to the symbol **412** but that the device corresponding to the symbol **422** must communicate with the network access point (symbol **412**) via an intermediate node such as field device represented by the symbol **426**.

Referring again to FIG. **11**A, a principle **502** may correspond to the preference to route data through powered devices. In accordance with the principle **502**, the procedure **500** may attempt to bypass the device corresponding to the symbol **400** because this device is battery-powered. However, the procedure **500** may decide whether this device should be bypassed also in view of the value the user has specified by means of the selector **467**. As indicated above, other factors may make the alternate nodes equally or more undesirable and the procedure **500** must use quantitative criteria when comparing the alternatives.

Next, the procedure **500** may proceed to defining the rest of the graphs while trying to keep the number of hops of each individual graph as low as possible. In one contemplated embodiment, the procedure **500** may initially construct a master graph which includes all potential wireless links irrespective of their quality. The procedure **500** may then consider each network device in sequence, traverse the initial master graph to identify all potential routes, and select the best candidates in view of the factors discussed above and other considerations. Specifically when applying a principle **506** to the initial master graph, the procedure **500** may select graphs with lower numbers of hops that also satisfy user requirements configured via the interactive screen **450**.

When choosing between neighbors of a particular device during path selection, the procedure **500** may apply a principle **508**, whereby a link with a better signal strength is given preference. However, the procedure **500** may not necessarily make a definite selection of paths upon considering the principles **502**-**508**. In a block **510**, the procedure **500** may assign numeric values, or weights, to each link according to the agreement of each link with one or more of the principles **502**-**508**. For example, the procedure **500** may multiply the weight of a link originating from a certain network device by the factor entered via the selector **467** because the network device is powered. On the other hand, the procedure **500** may increase the weight of a different link originating from the same network device because this link is part of a shorter path to the gateway, as measured by the number of hops. The procedure **500** may then select between the two links in a block **512** by executing a trivial comparison between the two numerical values.

The procedure **500** may apply the hop count and the neighbor count limitations while defining graphs according to the principles **502**-**508**. In other words, the procedure **500** may check whether every path and link selection carried out at the block **512** is consistent with the every rule specified through the interactive screen **450**. Alternatively, the procedure **500** may apply the hop count and neighbor count limitations in blocks **514** and **516**, respectively, upon completing the selection of weighted routes in the block **512**. In this case, the procedure **500** may eliminate some of the previously selected links and paths and return to the block **512**.

Further, the procedure **500** may try to select at least two paths for each device in the block **512**, for example, to ensure path redundancy. In other words, the procedure **500** may attempt to allocate at least one distinct duplicate path in addition to the selected primary path so that the duplicate path connects the same pair of devices. In this manner, a failure in one of the nodes of the primary path or an unexpected obstruction between a pair of nodes in the primary path will not necessarily prevent the devices from communicating. The network design tool **45** may indicate the availability of a redundant path connecting a field device to the gateway by coloring the corresponding symbol. FIG. **12** illustrates a network model which is generated by the network design tool **300** after a use has invoked the interactive window **450**, and after the network model **324** illustrated in FIG. **10** has been constructed. In particular, the user may have operated the threshold signal strength selector **455** to increase the threshold value. As a result, the network design tool **450** may have eliminated some of the duplicate links and the symbol **400** now appears in a different color than in FIG. **12**. By contrast, the symbol **426** appears in the original color because the symbol **426** appears as both a node in the path connecting the symbol **400** to the network access point symbol **412** and as a node in the path connecting the symbols **520** and **522** to the symbol **412**. Moreover, as illustrated in FIG. **12**, the device represented by the symbol **422** is now disconnected from the wireless HART network **14** because none of the links potentially connecting this device to its neighbors satisfies the new user requirements.

Referring now to FIG. **13**, the user may operate the obstacle button **392** to place an obstruction symbol **530** on the canvass area **382**. In one embodiment, the user may further customize the obstruction by stretching the symbol **530** or outlining an irregular shape using one of the well-known drawing means. In another embodiment, the user may further specify a signal attenuation factor of the obstacle represented by the symbol **530** by clicking on the symbol **530** and entering a numerical value in decibels via an obstacle configuration menu. In yet another embodiment, the user may additionally simulate a moving obstacle by specifying one or more animation parameters. It is contemplated that the network design tool **45** may simulate the disturbance caused by an obstacle moving at a specified speed in view of the burst rates of the devices affected by the obstruction. Of course, a device reporting measurements only once a minute may not "notice" an obstacle substantially cutting off the communication link of the device for only one or two seconds, while another device reporting measurements every second may fail to propagate one or several reports under the same set of conditions. Thus, some of the embodiments of the network design **450** may simulate the impact of both stationary and moving obstacles on various network devices.

FIGS. **13** and **14** illustrate one aspect of network simulation provided by the network design tool **45**. In FIG. **13**, the obstacle **530** is sufficiently removed from the network devices represented by symbols **400**, **412**, and **532** so as not to cause significant disturbance of the wireless links connecting these devices. On the other hand, in the state of the network model **324** illustrated in FIG. **14**, the same obstacle may effectively block the propagation of radio signals from the device corresponding to the symbol **400** to the network access point represented by the symbol **412**. As discussed above, FIGS. **13** and **14** may illustrate the network model either statically, in which case a stationary obstacle represented by the symbol **530** has been repositioned closer to the network nodes, or a snapshot of a transient state of the network model **324**, in which case a moving obstacle is temporarily interfering with the wireless link **416**. In either case, the network design tool **45** may calculate the impact of the simulated obstacle on the network model **342** and may delete the wireless link **416**.

In addition to generating and automatically adjusting graphs, the network design tool **45** may automatically generate schedules according to the optimization rules **306** and, optionally, user-specified parameters. FIGS. **14**A-**14**C illustrate several exemplary sequences of steps which the network design tool **45** and, in particular, the scheduler **304** may carry out as part of generating and optimizing the master schedule of the wireless HART network **14**. More specifically, the scheduler **304** may include procedures responsible for constraint enforcement, data superframe configuration, network management configuration, gateway superframe configuration, and special purpose superframe configuration.

Similar to the procedure **500**, a procedure **550** may apply at least some of the principles **552**-**572** simultaneously or may alter the sequence of applying the principles **552**-**572** to a master schedule being developed. The procedure **550** is primarily responsible for enforcing various design constraints on each individual schedule as well as on the master schedule. In a block **552**, the procedure **552** may apply the principle of limiting the number of concurrent channels. Of course, the number of concurrent channels is limited by the number of radio frequencies available to the wireless HART network **14**. In one contemplated embodiment, the user may configure the limit via the screen **450** or a similar interactive menu. Additionally, the network design tool **45** may include a relatively high hard-coded limit as a safeguard against configuration mistakes. For example, the absolute concurrent channel limit may be 16.

Next, the procedure **552** may apply a principle **554**, whereby no device may be scheduled to listen twice in the same time slot. In accordance to the next principle **556**, the procedure **552** may allow devices to receive data from multiple destinations. Referring back to the example illustrated in FIG. **11**, the device corresponding to the symbol **426** may receive data both from the device corresponding to the symbol **400** and from the device corresponding to the symbol **422**.

While applying the principle **558**, the procedure **552** will schedule early hops before later hops on a multi-hop network. In other words, the procedure **552** will attempt to minimize the latency on each multi-hop path by ensuring that each node has as many available timeslots as possible to forward a recently received data packet. For example, a node N**1** may receive a packet for N**2** in the timeslot with a relative number **5** in a 32-timeslot superframe. Thus, the node N**1** may have 27 potential timeslots in the remaining part of the superframe. The scheduler **304** may identify the next available timeslot within the superframe (such as 8, for example) and schedule the transmission from N**1** to N**2** to occur in that slot.

In order to optimize the alignment of superframes, the scheduler **304** may enforce the principle **560** requiring that all burst rates and, therefore, superframe sizes, conform with a predefined formula. For example, the burst rates may be defined as 2n seconds, where n is an integer. Thus, one network device may have a burst rate of 2-2 or four times a second, and another device may have a burst rate of 23 or once every 8 seconds. Further, the procedure **550** may ensure that the combined burst mode and network management communications do not exceed a predefined percentage of the total bandwidth available to the wireless HART network **14** (principle **562**). In one contemplated embodiment, this predefined percentage is set at 30%. Similarly, the procedure **550** may ensure, in accordance with the principle **564**, that none of the schedules exceeds a predefined ratio, such as 50%, of the total number of available timeslots. In this manner, the scheduler **304** attempts to reserve a sufficient number of free slots for such purposes as retries and other unplanned transmissions.

Referring now to FIG. **14**B, the procedure **565**, which is responsible for data superframe configuration, may apply a principle **566** and assign network devices to channel offsets starting with slot **0**. Next, the procedure **565** may allocate timeslots starting with the fastest scan rate (block **568**). By starting with the fastest scan rate, the scheduler **304** ensures that higher bandwidth demands are satisfied first because it is generally easier to find available timeslots for those devices which transmit infrequently and thus have lower scan rates.

For each path, the procedure **565** may start slot allocation from a device farthest from the gateway (block **570**). In particular, the procedure **565** may allocate one slot on the path to the gateway device, move on to the next hop in the path, and continue slot allocation until reaching the gateway. Upon successfully allocating each individual slot, the procedure may also allocate the closest available slot for a potential retry.

Once the procedure **565** allocates the timeslots for one path between each field device and the gateway, the scheduler **304** may additionally attempt to allocate timeslots on each duplicate path. As discussed above, a duplicate path connects the same pair of devices as the primary path but is distinct from the primary path in at least one intermediate hop. The procedure **550** attempts to allocate timeslots for the duplicate paths in a block **572**.

FIG. **14**C illustrates a procedure **580** which the scheduler **304** may execute after or in parallel with the procedures **550** and **565**. The procedure **580** is primarily responsible for management configuration. In particular, the procedure applies principles **582-590** to configure management superframes, principles **592-596** to configure the join process, and principle **598** to configure network management command propagation.

The principle **582** applied by the procedure **580** ensures that the network management superframes have higher priority than data superframes. Next, the procedure **580** may limit the size of the network management superframe to a predefined number such as 6000 slots in accordance with the principle **584**. Further, the scheduler **304** may assign the next priority to advertisement slots (principle **586**). Devices may use advertisement slots to join the wireless HART network **14**.

In a block **588**, the procedure **580** may perform a breadth-first search of the network graph and number the devices in the order in which the devices are encountered. Of course, the search corresponding to the block **588** may be performed at any time after the potential wireless links are defined. As mentioned above, the indicator **406** may conveniently display the number assigned to the device next to the corresponding device symbol. Because the user may add device symbols to the canvass area **382** in any order, the procedure **580** may need to renumber devices whenever new objects are added to the network model **324**.

Next, the procedure **580** may allocate slots for keep-alive messages. In general, every network device preferably has a timeslot reserved for keep-alive transmission. If a neighbor of the device does not propagate information through the device within a predefined time interval (such as 60 seconds), the device may send a keep-alive packet to the neighbor in order to verify the operational state of the neighbor.

The procedure **580** may also configure the join process by allocating slots reserved for join requests in a block **592**. For each path, the procedure **580** may start from the device farthest from the gateway and advance toward the gateway along the path. In some contemplated embodiments, the procedure **580** does not provide redundancy to join request time slots. Next, the procedure **580** may similarly allocate slots for join responses; however, the procedure may now start from the gateway and move in the direction of the device farthest from the gateway. The procedure **580** may then allocate advertise packets in each device in a block **596**. In one contemplated embodiment, the number of advertise packets allocated to a particular device is inversely related to the number of hops separating the device from the gateway.

In accordance with a principle **598**, the procedure **580** may configure sharing of network management links with join requests and join responses. This approach will allow the scheduler **304** to use the same set of links for two distinct purposes.

The scheduler **304** may generate a master schedule including the individual schedules of the devices of the wireless HART network **14** in accordance with the principles and strategies discussed above. The network design **45** may then provide several views **356-360** which the user may select by means of the schedule submenu **348**. FIG. **15** illustrates an exemplary schedule presented in a graph mode.

A graphical chart **620** may include a time slot grid **622**. In the exemplary embodiment depicted in FIG. **15**, each vertical line of the grid **622** corresponds to 5 timeslots. One of ordinary skill in the art will appreciate that the grid **622** may also include any scale convenient for the user, including an adjustable or enlargeable scale. A channel schedule listing **625** and a device schedule listing **627** may be disposed on the grid **622** in a horizontal direction. In other words, the network device tool **45** may depict the partitioning of channels into timeslots and the association of devices with timeslots as a horizontal time progression, with vertical lines representing consecutive 5-slot intervals. Further, each individual channel and each individual device may have a separate horizontal strip unambiguously showing timeslot allocation for the individual channel or device.

A legend **630** may illustrate the association of time slot assignments with one or more colors. Of course, the network device tool **45** may also use other methods of graphically specifying the state of each timeslot, such as using different shapes or symbols or, if the monitor **318** does not support multiple colors, by different shading techniques. In the example illustrated in FIG. **15**, the legend **630** instructs the user that vertical bars of a color **632** represent timeslots reserved for exclusive use by a pair of devices and that vertical bars of color **634** represent timeslots allocated for shared use by multiple devices. The channel listing **625** includes blank spaces corresponding to unassigned timeslots and vertical bars of colors **632** and **634**. In the example illustrated in FIG. **15**, the chart **620** indicates by means of blank spaces and colored bars that channel **3** is scheduled for shared transmission in timeslot **11** and for exclusive transmissions in timeslots **0**,**1**,**3**,**5**,**7**,**10**,**14**, **19**, **35**, and **39**, and that the rest of the timeslots on channel **3** are available.

On the other hand, the device schedule listing **627** includes, in addition to blank spaces similarly corresponding to unassigned timeslots, vertical bars of colors **636** and **638**. According to the exemplary legend **630**, vertical bars of color **636** represent timeslots reserved for reception and vertical bars of color **638** represent timeslots reserved for transmission. In the example illustrated in FIG. **15**, the chart **620** indicates that the device **11** is scheduled for transmission in timeslots **0** and **7** and for reception in timeslots **32**, **34**, and **39**.

In some situations, the user may prefer to view the network schedule in a text format or in an XML format instead. FIG. **16**A illustrates a screen **650** listing a network schedule as a series of expandable XML tags. In this example, FIGS. **16**A and **17** correspond to the same network schedule of a network model which may similar but not identical to the network model **324**. Referring to FIG. **16**B, a screen **652** contains an expanded schedule for device **3**. In addition to presenting a textual alternative to the graphical chart **620**, the screen **650** and **652** may also present additional information regarding the schedules. In particular, the screen **652** includes a link-by-link listing of slot allocation for several superframes in which device **3** participates (panes **655** and **657**).

Similarly, the network design tool **45** may also display routing information in the XML format. FIG. **17** illustrates an exemplary XML listing **670** of a topology of the network model **324**. Each of the device panes **672** may display such essential information as device type, logical device address, and full device address on a bar **674**. In the expanded mode, each pane may further display neighbor information in a neighbor pane **680** and graph information in graph panes **682**. For each neighbor, the XML listing **670** may include signal quality indicator **684** next to the device address **686**.

In operation, the network design tool **45** may generate the initial routing and scheduling information based on user input entered via the interactive screens **380** and **450** and in view of the predefined optimization rules **306**. The network design tool **45** may reassess the initial graphs and schedules based on the feedback information regarding the performance of the wireless HART network **14** received via the live network interface **320**. In this sense, the network model **324** corresponding to the wireless network **14** is an adaptive and automatically adjustable model. Further, the network design tool **45** may also adjust the network model **324** due to changes in one or more user preferences which the user may indicate by removing or adding network device and obstacle symbols to the canvass area **382** or by changing various parameters by means of the interactive screen **450**.

In particular, the user may use the network design tool **45** solely for the purpose of simulating a wireless HART network. For example, a process control engineer, or other user, may explore the general utility of installing a wireless HART network in a certain environment or the efficiency of a contemplated design of a wireless HART network. By using the interactive screens **380** and **450**, as well as other functions of the network design tool **45** discussed above, the user may build a network model by placing symbols representing routers, field devices, gateways, access points, obstructions to radio signals, and other relevant devices and objects in a canvass area, and easily evaluate various potential arrangements of the actual hardware. Because the user may easily move, add, and delete symbols representing devices and various objects, the user may efficiently and accurately assess the impact of such engineering decisions as, for example, reducing the fleet of routers or adding additional network access points. As indicated above, the user may also parameterize each simulated device. One familiar with the process control industry will appreciate that various devices may have different operational parameters due to the differences in device manufacturer, price, class and type of a device, as well as age of a device, power requirements of a device, and a number of other factors. Thus, in addition to assessing the difference of a certain physical arrangement relative to an alternate arrangement, the user may further assess the impact of substituting a more powerful device for a less powerful device performing a similar function, to take one example. By comparing the impact of the contemplated substitution on the simulated performance in view of such factors as the difference in price and in complexity of installation between the two alternatives, the user may make a highly informed decision and, ultimately, arrive at a better network design.

Importantly, the user of the network design tool **45** may enjoy a high level of confidence with respect to the correspondence between the network model and an actual physical wireless HART network constructed in accordance with the model. Because the routing and scheduling decisions of a wireless HART network are preferably centralized in the network manager **27**, the network design tool **45** and the network manager **27** may use a similar engine **300** to carry out such functions as graph and schedule definition, graph and schedule adaptation, and other configuration decisions. It is further contemplated that the engine **300** may be provided as a software library or software object with a set of standard interfaces so that both the network manager **27** and the network design tool **45** may instantiate identical engine **300** objects inside their respective software frameworks. In some embodiments, the engine **300** may configure, adjust, and otherwise manage a network without knowing whether the network is actual (such as the wireless HART network **14**) or simulated (such as the network model **324**). Of course, this embodiment may further involve a module generating "dummy" burst data, dummy network management requests and other simulated data working in co-operation with (or within) the network design tool **45** in order to supply simulated network traffic to the shared engine **300**.

Clearly, using the same engine **300** or, at least, some of the same components in the network manager **27** and the network design tool **45** may significantly improve the reliability of simulation. Additionally, the user may use the animation capability of the network design tool **45** to evaluate the performance of a network model over a certain period of time and, in particular, the periods when obstacles are present in the area in which the physical wireless network may operate. As discussed above, the user may simulate both the attenuation strength and the movement parameters of the obstacle, such as speed and direction. A further advantage afforded by the network design tool **45** is that the user may observe the impact of the obstacles on the simulated network visually, in an easy to understand manner. Of course, the network design tool **45** may also provide visualization to all aspects of the operation of a network model and thus of a physical wireless network. One skilled in the art will appreciate that a visual depiction of a network graph or a visual representation of a schedule may simplify the evaluation of the quality of the network model. For example, the user is more likely to recognize an inefficient path resulting from a poor arrangement of network devices if the user can view the resulting graph in a visual manner.

On the other hand, the user may further improve an existing network model by using feedback data from an actual physical network. For example, the user may have developed an initial network model and implemented the wireless HART network **14** according to the initial model. Of course, some of the physical devices may not perform in precisely the same manner as their corresponding simulacra in the network model. In particular, some of devices may detect a lower than simulated signal strength, such as 4 dB instead of the simulated 6 dB. Similarly, the wireless HART network **14** may measure the actual latency of a certain path to be 5 ms while the simulated latency of the same path is 4 ms. Moreover, the wireless HART network **14** may discover a large amount of interference on a certain channel and may, as a result, blacklist the channel and the corresponding carrier frequency. The network design tool **45** may retrieve this and other available data from the wireless HART network **14** by means of the live network interface **320** discussed above and may automatically adjust the network model. In some embodiments, the network design tool **45** may always "prefer" data from the live network interface **320** and may override the simulated parameters whenever actual data is available. Of course, some of the live data may not be always available if, for example, a certain part of the wireless HART network **45** is not yet installed or if parts of the corresponding plant are undergoing maintenance.

In this sense, the network design tool **45** may combine network simulation with live data received from the wireless HART network **14** in real time. The network design tool **45** may effectively synchronize the simulation with the live wireless HART network **14** for the parts of the network where live data is available. Meanwhile, the user may contemplate adding or removing certain network devices to the wireless HART network **14** and, in order to efficiently assess the impact of the contemplated changes on the live network, he or she may first update the network model by using the network design tool **45**. In at least some of the embodiments, the network design tool **45** may recognize that although the network model does not fully correspond to a live wireless HART network reporting performance related data via the interface **320**, some of the data may still be used to adjust the network model. Thus, the user may efficiently and accurately estimate the impact of adding, removing, or reconfiguring a network device on a physical network prior to actually adding, removing, or reconfiguring the device. Moreover, it is contemplated that the user may also re-arrange the existing rule priority or choose a different topology with respect to the network model which uses live feedback data. The network design tool **45** may simulate the new set of rules or the new topology by using the feedback data reported from the physical network. In this sense, the user may quickly and accurately estimate the impact of major system-wide changes on a live network in addition to more minor, device-specific changes.

It is also contemplated that the user may use the network design tool **45** in cooperation with a live network in order to populate various device specific parameters in the network model **324**. In particular, the user may construct the network model **324**, connect to an operation wireless HART network (such as the network **14**), and direct the network design tool **45** to obtain burst rates, signal strength measurements, latency measurement, and other data from the operational wireless HART network. In this manner, the user may reduce the time required to set up a network model, as well as achieve other advantages.

Although the forgoing text sets forth a detailed description of numerous different embodiments, it should be understood that the scope of the patent is defined by the words of the claims set forth at the end of this patent and their equivalents. The detailed description is to be construed as exemplary only and does not describe every possible embodiment because describing every possible embodiment would be impractical, if not impossible. Numerous alternative embodiments could be implemented, using either current technology or technology developed after the filing date of this patent, which would still fall within the scope of the claims.

What is claimed is:

1. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system, the system comprising:

an output module that provides network configuration data as an output, the network configuration data including a communication schedule for a plurality of devices coupled to a wireless communication network;

an interface module (i) to receive input data provided by a user that describes the plurality of devices coupled to the wireless communication network without describing a timing of communications between the plurality of devices, and (ii) to store the input data on a computer-readable medium,

the plurality of devices including one or more field devices configured to perform control or measurement functions for a process controlled within a process control plant, and

the wireless communication network communicatively coupled to a plant automation network of the process control plant; and

an engine module communicatively coupled to the interface module to generate the network configuration data using the input data and a set of rules associated with a wireless communication scheme, wherein the network configuration data is used to configure the wireless communication network;

wherein the generated network configuration data includes the communication schedule, wherein the communication schedule is generated according to the input data provided by the user and defines the timing of communications between the plurality of devices.

2. The computer-readable medium of claim **1**, wherein the input data includes geographic information related to at least some of the plurality of devices, wherein the geographic information is indicative of a physical location of one of the plurality of devices relative to at least another one of the plurality of devices.

3. The computer-readable medium of claim **1**, wherein the input data includes a device type for at least one of the plurality of devices; wherein the at least of the one of the plurality of devices is one of:

a one of the one or more field devices;

a router device that routes data between at least two of the plurality of devices without consuming or originating process control data;

a gateway device that connects the wireless communication network to an external host; or

a wireless access point that communicates with at least another of the plurality of devices in a wireless manner and with a gateway device in a wired manner.

4. The computer-readable medium of claim **1**, wherein the input data includes at least one of the following for at least one of the plurality of devices:

a burst rate corresponding to a rate of reporting measurements associated with process control to another one of the plurality of devices;

a power supply type corresponding to one of a permanent power source or a non-permanent power source supplying power to the at least one of the plurality of devices; or

a signal strength corresponding to a strength of a radio signal transmitted from the at least one of the plurality of devices.

5. The computer-readable medium of claim **1**, wherein the wireless communication scheme corresponds to a wireless Highway Addressable Remote Transmitter (HART®) communication protocol that shares a common application layer with a wired HART communication protocol used by the plant automation network.

6. The computer-readable medium of claim **1**, wherein the network configuration data further includes a routing scheme defining a set of communication routes between the plurality of devices;

wherein the input data includes geographic information for each of the plurality of devices; and

wherein the engine module includes: a graph generator to define direct wireless connections between pairs of the plurality of devices as a part of the routing scheme using the geographic information.

7. The computer-readable medium of claim **1**, wherein the network configuration data further includes a routing scheme defining a set of communication routes between the plurality of devices;

wherein each communication route in the set of communication routes includes a directed graph connecting a pair of the plurality of devices via one or several direct wireless connections;

wherein the engine module includes: a graph generator to generate a set of directed graphs using the input data.

8. The computer-readable medium of claim **7**, wherein the interface module includes:

a parameter selection routine to specify at least one of:

a maximum number of intermediate devices to be associated with each one of the set of directed graphs;

a maximum number of devices to consider as candidates for establishing a direct wireless connection to any one of the plurality of devices; or

a signal strength difference value for selecting between a first communication path connecting a pair of the plurality of devices and having a first number of intermediate devices and a second communication path connecting the pair of the plurality of devices having a second number of intermediate devices greater than the first number, wherein the signal strength difference corresponds to an amount by which signal strength associated of the second communication path must exceed signal strength associated with the first communication path to prefer the second communication path to the first communication path.

9. The computer-readable medium of claim **1**, wherein the engine module includes:

an Extended Mark-up Language (XML) generator to generate an XML description of the communication schedule.

10. The computer-readable medium of claim **1**, wherein each of the plurality of devices communicates wirelessly with at least another one of the plurality of devices along a corresponding direct wireless connection; and wherein the engine module comprises:

a schedule generator to allocate a plurality of timeslots associated with a plurality of communication channels to the plurality of direct wireless connections as a part of the communication schedule.

11. The computer-readable medium of claim **1**, wherein the engine module uses the input data to generate a network model; wherein the network model includes a plurality of nodes each corresponding to one of the plurality of devices; and wherein the interface module includes:

a node addition routine to add a node to the plurality of nodes;

a node removal routine to remove a node from the plurality of nodes; and

a node positioning routine to associate one of the plurality of nodes with a geographical position relative to at least another one of the plurality of nodes; wherein each of the node addition routine, the node removal routine, and the node positioning routine is responsive to user input.

12. The computer-readable medium of claim **1**, wherein the engine module uses the input data to generate a network model; and wherein the interface module communicates with an input device to receive user commands to edit the network model; and wherein the output module interacts with a display device to render a representation of the network model thereon.

13. The computer-readable medium of claim **12**, wherein the engine module defines a set of direct wireless connections between pairs of the plurality of devices using the input data; and wherein the interface module includes:

a graphical user interface (GUI) routine to display the plurality of devices as a plurality of nodes interconnected by the set of direct connections.

14. The computer-readable medium of claim **1**, wherein the input data includes information indicative of a physical location of a first one of the plurality of devices and a second one of the plurality of devices; and wherein the engine module estimates a quality of a wireless signal transmitted from the first one of the plurality of devices and measured at the second one of the plurality of devices using the physical location information of the first one of the plurality of devices and the second one of the plurality of devices.

15. The computer-readable medium of claim **1**, wherein the interface module is a first interface module, and wherein the system further comprises:

a second interface module to receive live performance data from the wireless communication network; wherein the engine module generates the network configuration data further using the live performance data.

16. The computer-readable medium of claim **15**, wherein the live performance data includes a measurement related to at least one of:

a signal strength at one of the plurality of devices; or

a delay associated with propagating a message from a first one of the plurality of devices to a second one of the plurality of devices.

17. The computer-readable medium of claim **1**, wherein the generated network configuration data further includes:

a routing scheme, generated according to the input data provided by the user, including a selection of a set of wireless links between pairs of the plurality of devices in view of wireless link quality and a definition of a set of communication routes between the plurality of devices.

18. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system, the system comprising:

an interface module (i) to receive input data provided by a user describing a plurality of devices coupled to a wireless communication network and (ii) to store the input data on a computer-readable medium,

the plurality of devices including one or more field devices configured to perform control or measurement functions for a process controlled within a process control plant, and

the wireless communication network communicatively coupled to a plant automation network of the process control plant; and

an engine module communicatively coupled to the interface module to generate network configuration data using the input data and a set of rules associated with a wireless communication scheme, wherein the network configuration data is used to configure the wireless communication network;

wherein the generated network configuration data includes:

a communication schedule, generated according to the input data provided by the user, that defines a timing of communications between the

plurality of devices; and

the system further comprising:

an output module that provides the network configuration data as an output;

wherein the engine module uses the input data to generate a network model; wherein the network model includes a plurality of nodes each corresponding to one of the plurality of devices; and wherein the interface module includes:

a node addition routine to add a node to the plurality of nodes;

a node removal routine to remove a node from the plurality of nodes;

a node positioning routine to associate one of the plurality of nodes with a geographical position relative to at least another one of the plurality of nodes; wherein each of the node addition routine, the node removal routine, and the node positioning routine is responsive to user input;

a power source type selection routine to associate a specified one of the plurality of nodes with one of a first type of a power source or a second type of a power source; and

a power factor selection routine to associate the first type with a first value of a power factor and the second type with a second value of the power factor; and wherein the engine module includes:

a graph generator to generate a set of directed graphs using the power factor associated with each of the plurality of devices.

19. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system, the system comprising:

an interface module (i) to receive input data provided by a user describing a plurality of devices coupled to a wireless communication network and (ii) to store the input data on a computer-readable medium,

the plurality of devices including one or more field devices configured to perform control or measurement functions for a process controlled within a process control plant, and

the wireless communication network communicatively coupled to a plant automation network of the process control plant; and

an engine module communicatively coupled to the interface module to generate network configuration data using the input data and a set of rules associated with a wireless communication scheme, wherein the network configuration data is used to configure the wireless communication network;

wherein the generated network configuration data includes:

a communication schedule, generated according to the input data provided by the user, that defines a timing of communications between the plurality of devices; and

the system further comprising:

an output module that provides the network configuration data as an output;

wherein the engine module uses the input data to generate a network model; wherein the network model includes a plurality of nodes each corresponding to one of the plurality of devices; and wherein the interface module includes:

a node addition routine to add a node to the plurality of nodes;

a node removal routine to remove a node from the plurality of nodes;

a node positioning routine to associate one of the plurality of nodes with a geographical position relative to at least another one of the plurality of nodes; wherein each of the node addition routine, the node removal routine, and the node positioning routine is responsive to user input; and

a topology selection routine to select a topology for the plurality of nodes including a mesh configuration, star configuration, or a mesh star configuration; wherein the engine module defines direct wireless connections between pairs of the plurality of devices to generate a routing scheme of the wireless communication network in accordance with the selected topology.

20. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system, the system comprising:

an interface module (i) to receive input data provided by a user describing a plurality of devices coupled to a wireless communication network and (ii) to store the input data on a computer-readable medium,

the plurality of devices including one or more field devices configured to perform control or measurement functions for a process controlled within a process control plant, and the wireless communication network communicatively coupled to a plant automation network of the process control plant; and

an engine module communicatively coupled to the interface module to generate network configuration data using the input data and a set of rules associated with a wireless communication scheme, wherein the network configuration data is used to configure the wireless communication network;

wherein the generated network configuration data includes:

a communication schedule, generated according to the input data provided by the user, that defines a timing of communications between the plurality of devices; and

the system further comprising:

an output module that provides the network configuration data as an output;

wherein the engine module uses the input data to generate a network model; wherein the network model includes a plurality of nodes each corresponding to one of the plurality of devices; and wherein the interface module includes:

a node addition routine to add a node to the plurality of nodes;

a node removal routine to remove a node from the plurality of nodes;

a node positioning routine to associate one of the plurality of nodes with a geographical position relative to at least another one of the plurality of nodes; wherein each of the node addition routine, the node removal routine, and the node positioning routine is responsive to user input; and

a threshold input routine to associate a specified one of the plurality of nodes with a threshold signal strength value; and wherein the engine module includes:

a graph generator that defines a unidirectional wireless connection to the specified one of the plurality of nodes corresponding to a destination from another one of the plurality of nodes corresponding to a source only if a projected strength of a signal from the source to the destination exceeds the threshold signal strength.

21. A computer-implemented method of designing a wireless mesh communication network for a process control environment using network configuration data that includes a communication schedule for a plurality of wireless devices, the method comprising:

obtaining input data provided by a user, the input data descriptive of the plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network but not descriptive of a timing of communications for the plurality of wireless devices, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wirelessly communicate in the process control environment, including:

defining, according to the input data provided by the user, the communication schedule of the wireless mesh communication network, wherein the communication schedule defines the timing of communications for the plurality of wireless devices; and

the method further comprising:

providing the network configuration data as output.

22. The method of claim **21**, wherein obtaining the input data for each of the plurality of wireless devices includes:

receiving a device type indication corresponding to one of a predefined types of a wireless device from the plurality of wireless devices; and

receiving a location indication corresponding to a physical location of the wireless device from the plurality of wireless devices relative to the plurality of devices.

23. The method of claim **22**, wherein receiving the device type indication includes receiving the device type indication corresponding to one of: the at least one field device, a router device that routes process control data originated by a first one of the plurality of devices and addressed to another one of the plurality of devices, a gateway device that connects the wireless mesh communication network to an external host, or a wireless access point that communicates with at least another of the plurality of devices in a wireless manner and with a gateway device in a wired manner.

24. The method of claim **22**, wherein obtaining the input data for each of the plurality of wireless devices further includes:

receiving a power level indication corresponding to a power level of a wireless signal transmitted by the wireless device from the plurality of wireless devices.

25. The method of claim **21**, wherein obtaining the input data includes:

providing a display interface to the user, comprising:

providing a canvass area on the display; and

providing an interactive menu having a plurality of user selectable functions including at least a first function to add a representation of a device to a selected location within the canvass area and a second function to remove a selected representation of a device from the canvass area.

26. The method of claim **25**, wherein providing the interactive menu further includes providing a third function to add a representation of an obstacle to a selected location within the canvass area; wherein the obstacle positioned between a first one of the plurality of devices and a second one of the plurality of devices attenuates a wireless signal transmitted between the first and second devices.

27. The method of claim **21**, further comprising generating a set of graphs, including generating a set of directed graphs connecting pairs of the plurality of devices.

28. The method of claim **27**, further comprising:

displaying at least one of a graphical representation or a textual representation of the plurality of devices and of the set of directed graphs on a display interface.

29. The method of claim **27**, wherein defining the communication schedule of the wireless mesh communication network includes allocating a plurality of timeslots associated with a set of wireless channels to the plurality of devices to define a communication schedule of the wireless mesh communication network.

30. The method of claim **27**, wherein obtaining the input data for at least some of the plurality of devices includes:

obtaining a power level indication corresponding to a power level of a transmitted wireless signal; and wherein generating a set of directed graphs connecting pairs of the plurality of devices includes:

defining a plurality of direct wireless connections between pairs of the plurality of devices, comprising:

evaluating a plurality of potential direct wireless connections at each of the plurality of devices by calculating a strength of a signal received at each of the plurality of devices from another one of the plurality of devices using the corresponding power level indication; and

selecting direct wireless connections from the plurality of potential direct wireless connections based on at least the calculated strength of the signal; and

associating a subset of the plurality of direct wireless connections with each directed graph in the set of directed graphs.

31. The method of claim **21**, further comprising:

receiving feedback data from the wireless mesh communication network; and

updating the generated network configuration data based on the received feedback data.

32. The method of claim **31**, wherein receiving the feedback data includes receiving a set of measurements of data propagation delay in the wireless mesh communication network.

33. The method of claim **31**, wherein receiving the feedback data includes receiving a set of signal strength measurements from at least some of the plurality of devices.

34. The method of claim **21**, further comprising:

providing a display interface to the user;

receiving a design constraint from the display interface; and wherein

the defining the communication schedule of the wireless mesh communication network includes defining the communication schedule of the wireless mesh communication network in view of the design constraint.

35. The method of claim **21**, wherein automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wireles sly communicate in the process control environment further includes:

generating a set of graphs to define a routing scheme of the wireless mesh communication network.

36. A computer-implemented method of designing a wireless mesh communication network for a process control environment, the method comprising:

obtaining input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wirelessly communicate in the process control environment, including:

defining, according to the input data provided by the user, a communication schedule of the wireless mesh communication network; and

the method further comprising: providing the network configuration data as output;

wherein obtaining the input data for each of the plurality of wireless devices includes:

(i) receiving a device type indication corresponding to one of a predefined types of each of the plurality of wireless devices; and

(ii) receiving a location indication corresponding to a physical location of each of the plurality of wireless devices relative to the plurality of devices;

wherein obtaining the input data for each of the plurality of wireless devices further includes: receiving a power source selection indicative of type of a power source that supplies power to the device.

37. A computer-implemented method of designing a wireless mesh communication network for a process control environment, the method comprising:

obtaining input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wirelessly communicate in the process control environment, including:

defining, according to the input data provided by the user, a communication schedule of the wireless mesh communication network; and the method further comprising:

providing the network configuration data as output;

wherein obtaining the input data includes:

(i) providing a display interface to the user,

(ii) providing a canvass area on the display; and

(iii) providing an interactive menu having a plurality of user selectable functions including at least a first function to add a representation of a particular device to a selected location within the canvass area and a second function to remove the representation of the particular device from the canvass area;

wherein providing the interactive menu further includes providing a third function to specify a rate at which the particular device originates process control data.

38. A computer-implemented method of designing a wireless mesh communication network for a process control environment, the method comprising:

obtaining input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wirelessly communicate in the process control environment, including:

defining, according to the input data provided by the user, a communication schedule of the wireless mesh communication network; and the method further comprising:

(i) providing the network configuration data as output; and

(ii) generating a set of graphs, including generating a set of directed graphs connecting pairs of the plurality of devices;

wherein the plurality of devices includes a gateway device to communicate with a host external to the wireless mesh communication network; and wherein generating the set of directed graphs connecting pairs of the plurality of devices includes:

(a) generating a first set of upstream directed graphs connecting each of the plurality of devices with the gateway device; and

(b) generating a second set of downstream directed graphs connecting the gateway device to each of the plurality of devices.

39. A computer-implemented method of designing a wireless mesh communication network for a process control environment, the method comprising:

obtaining input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wirelessly communicate in the process control environment, including:

defining, according to the input data provided by the user, a communication schedule of the wireless mesh communication network; and the method further comprising:

providing the network configuration data as output; the method further comprising:

(i) providing a display interface to the user; and

(ii) receiving a design constraint from the display interface;

wherein applying the set of rules to the input data includes generating a routing scheme and the communication schedule for the wireless mesh communication network in view of the design constraint;

wherein the design constraint includes one of a maximum number of intermediate devices associated with a directed graph connecting a pair of the plurality of devices; a maximum number of devices having a direct wireless connection to any one of the plurality of devices; or a minimum number of devices to consider at one of the plurality of devices when defining a directed graph from the one of the plurality of devices to another one of the plurality of devices.

40. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system for designing a wireless communication network for a process control environment using network configuration data that includes a communication schedule for a plurality of wireless devices, the system comprising:

a user interface module to receive input data provided by a user, the input data descriptive of the plurality of wireless devices associated with the process control environment but not descriptive of a timing of communications of the plurality of wireless devices, the plurality of wireless devices coupled to the wireless communication network and including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless communication network coupled to a plant automation network of the process control environment; and

an engine module communicatively coupled to the user interface module to automatically generate network configuration data using the input data for the plurality of wireless devices;

wherein the network configuration data is used to configure the plurality of wireless devices and includes the communication schedule, and wherein the communication schedule is defined according to the input data provided by the user to define the timing of communication of the plurality of devices; the engine module including:

a graph generator to define a plurality of direct wireless connections between pairs of the plurality of devices and to generate a set of directed graphs using the plurality of direct wireless connections; and

a schedule generator to associate a plurality of timeslots with a plurality of communication channels, and to allocate the plurality of timeslots to the plurality of direct wireless connections defined by the graph generator.

41. The computer-readable medium of claim **40**, wherein the wireless communication network applies a set of rules associated a wireless Highway Addressable Remote Transmitter (HART®)communication protocol to generate the network configuration data, the wireless HART communication protocol sharing a common application layer with a wired HART communication protocol used by the plant automation network.

42. The computer-readable medium of claim **40**, wherein the input data descriptive of the plurality of devices includes:

data corresponding to the at least one field device; and

data corresponding to a gateway device communicatively coupled to an external host operating outside the wireless communication network.

43. The computer-readable medium of claim **42**, wherein the user interface module includes a burst rate selection routine to associate a specified one of the plurality of devices with a rate of reporting measurements associated with process control to the gateway device.

44. The computer-readable medium of claim **40**, wherein the communication schedule includes:

a set of dedicated timeslots corresponding to an exclusive use by a pair of the plurality of devices on the corresponding communication channel; and

a set of shared timeslots corresponding to a shared use by two or more of the plurality of devices on the corresponding communication channel.

45. The computer-readable medium of claim **40**, wherein the generated network configuration data further includes:

a routing scheme defined according to the input data provided by the user as a set of communication paths connecting pairs of the plurality of devices.

46. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system for designing a wireless communication network for a process control environment, the system comprising:

a user interface module to receive input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and to store the input data on a computer-readable medium, the plurality of wireless devices coupled to the wireless communication network and including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless communication network coupled to a plant automation network of the process control environment; and

an engine module communicatively coupled to the user interface module to automatically generate network configuration data using the input data for the plurality of wireless devices; wherein the network configuration data is used to configure the plurality of wireless devices and includes a communication schedule defined according to the input data provided by the user to define timing of communication of the plurality of devices; the engine module including:

a graph generator to define a plurality of direct wireless connections between pairs of the plurality of devices and to generate a set of directed graphs using the plurality of direct wireless connections; and

a schedule generator to associate a plurality of timeslots with a plurality of communication channels, and to allocate the plurality of timeslots to the plurality of direct wireless connections defined by the graph generator;

wherein the communication schedule includes:

(i) a set of dedicated timeslots corresponding to an exclusive use by a pair of the plurality of devices on the corresponding communication channel; and

(ii) a set of shared timeslots corresponding to a shared use by two or more of the plurality of devices on the corresponding communication channel;

wherein the user interface module includes:

a graphical user interface (GUI) routine to graphically render the generated communication schedule, wherein the GUI renders a first set of dedicated timeslots using a first graphic and renders a second set of dedicated timeslots using a second graphic; wherein the first graphic and the second graphic differ in at least one of a color, a shape, or a size.

47. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a software tool for designing a mesh communication network that includes a plurality of devices operating in a process control plant, the tool comprising:

an interface module to facilitate, based on input data provided to the interface module by a user describing the plurality of devices without describing a timing of communications for the plurality of devices, creation or modification of an interactive model of the mesh communication network, wherein:

the interactive model is stored as data on a computer-readable medium,

the mesh communication network is coupled to a plant automation network of the process control plant, and

the plurality of devices is coupled to the mesh communication network and the plurality of devices includes at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control plant; and

an engine module communicatively coupled to the interface module to automatically generate a parameter set for operating the mesh communication network based on the interactive model, the parameter set including a communication schedule, the communication schedule generated according to the input data provided by the user and defining the timing of communications for the plurality of devices.

48. The computer-readable medium of claim **47**, wherein the parameter set is associated with at least one of a routing scheme of the mesh communication network or the communication schedule.

49. The computer-readable medium of claim **48**, wherein the engine module includes:

a graph generator to define direct wireless connections between pairs of the plurality of devices using at least a geographic information associated with each of the plurality of devices and stored as a part of the interactive model; wherein the routing scheme includes the defined direct wireless connections.

50. The computer-readable medium of claim **48**, wherein the engine module includes:

a graph generator to generate a set of directed graphs connecting pairs of the plurality of devices via one or several direct wireless connections to define the routing scheme of the mesh communication network.

51. The computer-readable medium of claim **47**, wherein the interface module includes:

a node addition routine to add a node to a plurality of nodes of the interactive model corresponding to the plurality of devices coupled to the mesh communication network;

a node removal routine to remove a node from the plurality of nodes; and

a node positioning routine to associate one of the plurality of nodes with a geographical position relative to at least another one of the plurality of nodes; wherein each of the node addition routine, the node removal routine, and the node positioning routine is responsive to user input.

52. The computer-readable medium of claim **47**, wherein the interface module includes:

a graphical user interface (GUI) routine to display the interactive model as a plurality of nodes interconnected by a set of direct connections corresponding to the parameter set generated by the engine module.

53. The computer-readable medium of claim **47**, wherein the generated parameter set further includes:

a routing scheme generated according to the input data provided by the user.

54. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system for use in configuring a wireless communication network for a process control plant, the system comprising:

an interface module to receive input data provided by a user describing a plurality of devices associated with the process control plant and to store the input data on a computer-readable medium, the input data including indications of relative distances between devices included in the plurality of devices, the plurality of devices including a field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control plant, the plurality of devices coupled to the wireless communication network, and the wireless communication network communicatively coupled to a plant automation network of the process control plant; and

an engine module communicatively coupled to the interface module to generate network configuration data using the input data and a set of rules associated with a wireless communication scheme, wherein the network configuration data is used to configure the wireless communication network;

wherein:

(i) the generated network configuration data includes at least one of:

a routing scheme including a selection of a set of wireless links between pairs of the plurality of devices in view of wireless link quality and a definition of a set of communication routes between the plurality of devices, and

a communication schedule that defines a timing of communications of the plurality of device;

(ii) the engine module uses the input data to generate a network model, wherein the network model includes a plurality of nodes each corresponding to one of the plurality of devices, wherein the interface module includes:

a node addition routine to add a node to the plurality of nodes; a node removal routine to remove a node from the plurality of nodes; and a node positioning routine to associate one of the plurality of nodes with a geographical position relative to at least another one of the plurality of nodes; wherein each of the node addition routine, the node removal routine, and the node positioning routine is responsive to user input; and

(iii) each one in the set of communication routes is a directed graph that includes at least direct wireless connection between a pair of the plurality of devices, wherein the interface module further includes:

a power source type selection routine to associate a specified one of the plurality of nodes with one of a first type of a power source or a second type of a power source; and

a power factor selection routine to associate the first type of with a first value of a power factor and the second type with a second value of the power factor; and wherein the engine module includes: a graph generator to generate a set of directed graphs using the power factor associated with each of the plurality of devices;

the system further comprising:

an output module that provides the network configuration data as an output.

55. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system for use in configuring a wireless communication network for a process control plant, the system comprising:

an interface module to receive input data provided by a user describing a plurality of devices associated with the process control plant and to store the input data on a computer-readable medium, the input data including indications of relative distances between devices included in the plurality of devices, the plurality of devices including a field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control plant, the plurality of devices coupled to the wireless communication network, and the wireless communication network communicatively coupled to a plant automation network of the process control plant; and

an engine module communicatively coupled to the interface module to generate network configuration data using the input data and a set of rules associated with a wireless communication scheme, wherein the network configuration data is used to configure the wireless communication network;

wherein:

(i) the generated network configuration data includes at least one of:

a routing scheme including a selection of a set of wireless links between pairs of the plurality of devices in view of wireless link quality and a definition of a set of communication routes between the plurality of devices, and

a communication schedule that defines a timing of communications of the plurality of device;

(ii) the engine module uses the input data to generate a network model, wherein the network model includes a plurality of nodes each corresponding to one of the plurality of devices, wherein the interface module includes:

a node addition routine to add a node to the plurality of nodes; a node removal routine to remove a node from the plurality of nodes; and a node positioning routine to associate one of the plurality of nodes with a geographical position relative to at least another one of the plurality of nodes; wherein each of the node addition routine, the node removal routine, and the node positioning routine is responsive to user input; and

(iii) the interface module further includes:

a topology selection routine to select a topology for the plurality of nodes including a mesh configuration, star configuration, or a mesh star configuration; wherein the engine module defines direct wireless connections between pairs of the plurality of devices to generate a routing scheme of the wireless communication network in accordance with the selected topology;

the system further comprising:

an output module that provides the network configuration data as an output.

56. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system for use in configuring a wireless communication network for a process control plant, the system comprising:

an interface module to receive input data provided by a user describing a plurality of devices associated with the process control plant and to store the input data on a computer-readable medium, the input data including indications of relative distances between devices included in the plurality of devices, the plurality of devices including a field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control plant, the plurality of devices coupled to the wireless communication network, and the wireless communication network communicatively coupled to a plant automation network of the process control plant; and

an engine module communicatively coupled to the interface module to generate network configuration data using the input data and a set of rules associated with a wireless communication scheme, wherein the network configuration data is used to configure the wireless communication network;

wherein:

(i) the generated network configuration data includes at least one of:

a routing scheme including a selection of a set of wireless links between pairs of the plurality of devices in view of wireless link quality and a definition of a set of communication routes between the plurality of devices, and

a communication schedule that defines a timing of communications of the plurality of device;

(ii) the engine module uses the input data to generate a network model, wherein the network model includes a plurality of nodes each corresponding to one of the plurality of devices, wherein the interface module includes:

a node addition routine to add a node to the plurality of nodes; a node removal routine to remove a node from the plurality of nodes; and a node positioning routine to associate one of the plurality of nodes with a geographical position relative to at least another one of the plurality of nodes; wherein each of the node addition routine, the node removal routine, and the node positioning routine is responsive to user input; and

(iii) the engine module uses the input data to generate a network model, wherein:

the interface module further includes a threshold input routine to associate a specified one of the plurality of nodes with a threshold signal strength value; and

the engine module includes a graph generator that defines a unidirectional wireless connection to the specified one of the plurality of nodes corresponding a destination from another one of the plurality of devices corresponding to a source only if a projected strength of a signal from the source to the destination exceeds the threshold signal strength;

the system further comprising:

an output module that provides the network configuration data as an output.

57. A computer-implemented method of designing a wireless mesh communication network for a process control environment, the method comprising:

obtaining input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network, the input data including an indication of a relative distance between a pair of wireless devices included in the plurality of wireless devices, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wirelessly communicate in the process control environment, including at least one of:

generating a set of graphs to define a routing scheme of the wireless mesh communication network, and

defining a communication schedule of the wireless mesh communication network; and

the method further comprising:

providing the network configuration data as output;

wherein:

(i) obtaining the input data for each of the plurality of wireless devices includes: receiving a device type indication corresponding to one of a predefined types of a particular device; and receiving a location indication corresponding to a physical location of the particular device relative to the plurality of devices; and

(ii) obtaining the input data for each of the plurality of wireless devices further includes receiving a power source selection indicative of type of a power source that supplies power to the particular device.

58. A computer-implemented method of designing a wireless mesh communication network for a process control environment, the method comprising:

obtaining input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network, the input data including an indication of a relative distance between a pair of wireless devices included in the plurality of wireless devices, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wirelessly communicate in the process control environment, including at least one of:

generating a set of graphs to define a routing scheme of the wireless mesh communication network, and

defining a communication schedule of the wireless mesh communication network; and

the method further comprising:

providing the network configuration data as output

wherein:

(i) obtaining the input data includes providing a display interface to the user, comprising: providing a canvass area on the display; and providing an interactive menu having a plurality of user selectable functions including at least a first function to add a representation of a particular device to a selected location within the canvass area and a second function to remove the representation of the particular device from the canvass area; and

(ii) providing the interactive menu further includes providing a third function to specify a rate at which the particular device originates process control data.

59. A computer-implemented method of designing a wireless mesh communication network for a process control environment, the method comprising:

obtaining input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network, the input data including an indication of a relative distance between a pair of wireless devices included in the plurality of wireless devices, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wirelessly communicate in the process control environment, including at least one of:

generating a set of graphs to define a routing scheme of the wireless mesh communication network, and

defining a communication schedule of the wireless mesh communication network; and

the method further comprising:

providing the network configuration data as output;

wherein:

(i) generating a set of graphs includes generating a set of directed graphs connecting pairs of the plurality of devices; and

(ii) the plurality of devices includes a gateway device to communicate with a host external to the wireless mesh communication network; and wherein generating the set of directed graphs connecting pairs of the plurality of devices includes:

generating a first set of upstream directed graphs connecting each of the plurality of devices with the gateway device; and

generating a second set of downstream directed graphs connecting the gateway device to each of the plurality of devices.

60. A computer-implemented method of designing a wireless mesh communication network for a process control environment, the method comprising:

obtaining input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and coupled to the wireless mesh communication network, the input data including an indication of a relative distance between a pair of wireless devices included in the plurality of wireless devices, the plurality of wireless devices including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless mesh communication network communicatively coupled to a plant automation network of the process control environment; and

automatically applying a set of rules associated with a communication scheme to the input data to generate network configuration data used to configure the plurality of wireless devices to wireles sly communicate in the process control environment, including at least one of:

generating a set of graphs to define a routing scheme of the wireless mesh communication network, and

defining a communication schedule of the wireless mesh communication network; and

the method further comprising:

providing the network configuration data as output;

providing a display interface to the user; and

receiving a design constraint from the display interface;

wherein applying the set of rules to the input data includes generating the routing scheme and the communication schedule for the communication network in view of the design constraint;

wherein the design constraint includes one of a maximum number of intermediate devices associated with a directed graph connecting a pair of the plurality of devices; a maximum number of devices having a direct wireless connection to any one of the plurality of devices; or a minimum number of devices to consider at one of the plurality of devices when defining a directed graph from the one of the plurality of devices to another one of the plurality of devices.

61. A tangible, non-transitory computer-readable medium having a set of instructions stored thereon, wherein the set of instructions, when executed on a processor, implement a communication modeling system for designing a wireless communication network for a process control environment, the system comprising:

a user interface module to receive input data provided by a user and descriptive of a plurality of wireless devices associated with the process control environment and to store the input data on a computer-readable medium, the input data including respective indications of one or more relative distances between wireless devices included in the plurality of wireless devices, the plurality of wireless devices coupled to the wireless communication network and including at least one field device configured to perform a control function within a process or to perform a measurement of the process, the process being controlled within the process control environment, and the wireless communication network coupled to a plant automation network of the process control environment; and

an engine module communicatively coupled to the user interface module to automatically generate network configuration data using the input data for the plurality of wireless devices; wherein the network configuration data is used to configure the plurality of wireless devices and includes a routing scheme defined as a set of communication paths connecting pairs of the plurality of devices and a communication schedule to define timing of communication of the plurality of devices; the engine module including:

a graph generator to define a plurality of direct wireless connections between pairs of the plurality of devices and to generate a set of directed graphs using the plurality of direct wireless connections; and

a schedule generator to associate a plurality of timeslots with a plurality of communication channels, and to allocate the plurality of timeslots to the plurality of direct wireless connections defined by the graph generator;

wherein:

(i) the communication schedule includes:

(a) a set of dedicated timeslots corresponding to an exclusive use by a pair of the plurality of devices on the corresponding communication channel, and

(b) a set of shared timeslots corresponding to a shared use by two or more of the plurality of devices on the corresponding communication channel; and

(ii) the user interface module includes:

a graphical user interface (GUI) routine to graphically render the generated communication schedule, wherein the GUI renders a first set of dedicated timeslots using a first graphic and renders a second set of dedicated timeslots using a second graphic; wherein the first graphic and the second graphic differ in at least one of a color, a shape, or a size.

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